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UNIVERSITY OF ALBERTA

THE IGNITION OF NEAT METHANOL AT SUB-ZERO TEMPERATURES USING A PULSED PLASMA JET IGNITOR

BY

JAMES R. DAWE ©

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND
RESEARCH IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE
OF

MASTER OF SCIENCE

DEPARTMENT OF ELECTRICAL ENGINEERING

EDMONTON, ALBERTA
FALL 1991

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MASTER OF SCIENCE

IN

ELECTRICAL ENGINEERING

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DEDICATION

This thesis is dedicated to those who dragged me out from time to time and restored a bit of sanity to life, including my friends Larry and Joann Klassen, Chris Kaulbars, Bill and Leslie Gillespie, Larry Gadallah, Larry Gagnon, Alex Mair, Hubert and Erna Johnson, Jim and Michelle Holowchak, Ginny St. Laurent, and Stan and Elizabeth Penttinen. But especially, it is dedicated, with love, to Mary E. Dawe, by turns friend, supporter, expert editor and painstaking proofreader, but first, last, and always, mother.

ABSTRACT

Methanol is one popular candidate for an alternate transportation fuel now being investigated. Methanol is clean burning, and obtainable from renewable or non-renewable resources. However, the adoption of neat or 100% methanol (M100), especially in northern climates, is hindered by its very poor cold-starting characteristics. The primary problem is that methanol's low vapour pressure decreases effectively to zero at temperatures below freezing, making ignition all but impossible in winter conditions.

The plasma jet ignitor (PJI), whose hot, turbulent puff can penetrate, heat, mix, and ignite a variety of flammable mixtures, offers one possible solution to the problem of cold starting an engine burning M100. Results of tests using a PJI for methanol cold starting have not been reported in the literature.

Three experiments were designed: two laboratory experiments determined operation and quantified the energy vs temperature relationship, while the third tested cold-starting a 1973 Volvo using a plasma jet ignitor system. In the lab experiments, cold M100 was repeatably ignited in a cold chamber at temperatures down to -24 °C using a PJI with energies of up to 10 Joules. The PJI operated well down to the temperature limit of the available equipment. Cold starts of the test car were achieved using energies of up to 10.8 Joules at temperatures down to -16 °C, a temperature lower than previously published results for unmodified engines burning M100. Test results from all experiments show a linear correlation for reliable ignition between decreasing temperatures and increasing energy. It is concluded that plasma jet ignitors are able to ignite neat methanol at sub-zero temperatures, that there is a well-defined relationship between temperature and energy required, that a PJI system was successful in engine cold-starting tests, and that these results are a point of departure for further research.

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TABLE OF CONTENTS

CHAPTER PAGE

1: INTRODUCTION AND LITERATURE REVIEW

1.1 Alcohol Fuel and Internal Combustion Engines 1
1.2 Methanol Fuel Cold Starting Techniques 9
1.3 Plasma Jet Ignition as a Cold Starting Aid 22

2: EXPERIMENTAL APPARATUS

2.1 Plasma Jet Ignitor 29
2.2 Enhanced Plasma Jet Ignitor 35
2.3 AC Power Supply 38
2.4 12 Volt DC Mobile Power Supply 41
2.5 Methanol Pool Experiment 45
2.6 Methanol Injector Experiment 51
2.7 Volvo In-Engine Experiment 56

3: EXPERIMENTAL STUDIES

3.1 COLD PLATE AND METHANOL POOL 65
3.2 COOLED METHANOL INJECTOR 68
3.3 VOLVO IN-ENGINE TESTS 81
3.3.1 Cold Starting Temperature Limit Tests With Standard and High Energy Ignition Systems and J-Gap Spark Plugs. 82
3.3.2 Cold Starting Temperature Limit Tests With High Energy Plasma Jet Ignition 88

TABLE OF CONTENTS

CHAPTER PAGE

4: DISCUSSION

4.1 GENERAL RESULTS 95

4.2 FUEL HEATING AND VAPOURIZATION 102

4.3 COMPRESSION HEATING 105

4.4 IGNITOR LIMITATIONS 108

4.5 METHANOL ENTRAINMENT IN THE PLASMA PLUME 109

4.6 THE ENHANCED PJI 110

4.7 SUMMARY 112

5: CONCLUSIONS 113

BIBLIOGRAPHY 119

APPENDIX 1: PLASMA JET IGNITOR EROSION 130

LIST OF FIGURES

FIGURE		PAGE
2.1	Plasma Jet Ignitor	30
2.2	AC Power Supply	39
2.3	12 VDC Mobile Power Supply	44
2.4	Cooled Aluminum Block	46
2.4a	Block Cooling System	47
2.5	Cooled Block Setup	48
2.6	Injector Cold Chamber	52
2.7	High Energy Distributor	58
3.1	Single Shot Ignition Probability of M100 Pool	66
3.2	Plasma Jet Ignition of M100 Droplets at -24 °C	73
3.3	Plasma Jet Ignition of M100 Droplets at -23 °C	74
3.4	Plasma Jet Ignition of M100 Droplets at -18 °C	75
3.5	Plasma Jet Ignition of M100 Droplets at -14 °C	76
3.6	Plasma Jet Ignition of M100 Droplets at -10 °C	77
3.7	Plasma Jet Ignition of M100 Droplets at - 5 °C	78
3.8	Combined Temperature Graph, Plasma Jet Ignition of M100 Droplets	79

LIST OF FIGURES

FIGURE PAGE

3.9 Energy-Temperature Profile, 80% Probability of M100 Droplet Ignition 80

3.10 Volvo on M100, Standard Ignition and Spark Plugs, Starting Test #1 84

3.11 Volvo on M100, Standard Ignition and Spark Plugs, Starting Test #2 85

3.12 Stored Energy vs Temperature, Individual Engine Starts 92

3.13 Individual And Average Values, Stored Energy vs Temperature, Engine Starts 93

3.14 Comparison of Average Stored Energies, Engine Starts and 80% Probable M100 Droplet Ignition 94

NOMENCLATURE AND ABBREVIATIONS

°BTDC	Degrees Before Top Dead Centre
CI	Compression Ignition
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CR	Compression Ratio
DI	Direct Injection
DISC	Direct Injection Stratified Charge
E100	Neat or 100% Ethanol (C_2H_5OH)
HC	Hydrocarbon; also Homogenous Charge
HCHO	Formaldehyde
M100	Neat or 100% Methanol (CH_3OH)
MON	Motor Octane Number
NO_x	Oxides of Nitrogen
PJI	Plasma Jet Ignitor
PPJ	Pulsed Plasma Jet
RON	Research Octane Number
SI	Spark Ignition
TCCS	Texaco Controlled Combustion System

PROPERTIES OF METHANOL CH_3OH

Auto-Ignition Temperature Range	464-470 °C
Boiling Points	65 °C @ 1.0 atm
	78 °C @ 2.0 atm
	105 °C @ 5.0 atm
	113 °C @ 6.8 atm
	126 °C @ 10.0 atm
	177 °C @ 20.0 atm
Cetane Number	0.5
Density	786.5 kg/m^3
Dielectric Constant	32.6
Energy Content	19.94 MJ/kg
	1.569 MJ/l
Flammability Limits	Low = 6.7
(volume % in air)	High = 36.0
Flashpoint	11 °C
Freezing Point	-97.6 °C (175.5 K)
Latent Heat of Evaporation	1101.1 kJ/kg
Molecular Weight	32.043
Octane Number, Motor	99
Octane Number, Research	113
Octane Number (RON+MON)/2	106
Specific Gravity	0.789
Specific Heat	2.54 kJ/kg•K
Stoichiometric Air-Fuel Ratio	6.46
Thermal Conductivity	0.202 W/m•K
Vapour Pressure @ 21 °C	13 kPa
Viscosity	0.00056 $N \cdot S/m^2$

Sources: Heath 1989; Jorgensen 1988;
Thring 1983; Bolz & Tuve 1973

CHAPTER 1: INTRODUCTION

1.1 ALCOHOL FUELS AND INTERNAL COMBUSTION ENGINES

Internal combustion engines are one of the world's major sources of air pollution. In 1968, automobiles in just one large city, Los Angeles, emitted an estimated 620,500 tonnes of hydrocarbons (HC), 3,467,500 tonnes of carbon monoxide (CO), and 226,300 tonnes of oxides of nitrogen (NO_x) (Devins 1982). In 1987, 18 major U.S. cities regularly declared air quality alerts; Los Angeles had 141 days worth (Ross 1990). If this level of emission is multiplied by the total number of the world's major cities, and by the number of years IC engines have been in widespread use, the total pollutant tonnage is truly astounding. The reduction of emissions from automobiles is therefore a major part of any effort to slow the "greenhouse effect" and other environmental degradation, so the search for clean alternative fuels and ways to use them is a large element of combustion research.

Adding to the need for alternate fuels is the fact that internal combustion engines use more than four billion litres of gasoline daily, or roughly one third of the world's total annual petroleum production (Keck 1982). (Cheremisinoff et al. estimated annual 1990 gasoline demand at 517 billion litres in the U.S. alone). In 1982 the

United States spent over 85 billion dollars on oil imported from the OPEC nations; per-capita figures for European nations are similar (McGeer et al. 1982). This is a heavy annual economic burden on oil-consuming countries, one which will increase if shortages again occur, causing price increases. With petroleum becoming ever more vital as a petrochemical and manufacturing feedstock, burning it as fuel is also becoming harder to justify. Couple all of this to the political instability in many oil producing areas, and the search for viable alternatives to gasoline assumes more importance than ever.

With supply, economic, and environmental factors to consider, one major interest in alternate fuels research is supplementing or replacing gasoline (and possibly Diesel as well) with fuel alcohol. The possible use of methanol, or methyl alcohol (CH_3OH), is receiving attention and research funding from many North American agencies, including Transport Canada and the United States Environmental Protection Agency (EPA). Many other national governments worldwide are following suit, as are regional and municipal governments. For example, the City of Edmonton is now conducting experimental trials with a methanol fuelled bus, built by Flyer Industries of Winnipeg and engined by Detroit Diesel (Loyie 1991).

Ethanol (C_2H_5OH), is another possible choice for an alternative fuel, both in North America and elsewhere.

Brazil, in particular, has invested massive government resources in ethanol as a motor vehicle fuel ever since the 1930's, under a program called Proalcool (Pischinger et al. 1982). Brazil's motivation for converting to alcohol was strictly economic: it cut foreign oil imports, reduced foreign debt, and enlarged the domestic sugar cane and automobile industries. Since 1982, over 4 million Brazilian-built cars burning neat (100%) ethanol have been built; these now constitute 50% of all cars in use, and virtually all of the new cars sold (Brazil 1990; LoRusso et al. 1988). Most other Brazilian cars run on E20, a blend of 20% alcohol and 80% gasoline. Unfortunately, ethanol demand has recently exceeded production. Coupled with the volatile political climate in Brazil and large government debt, this shortage has resulted in frequent supply disruptions and a lessening of faith in the Proalcool program (Brazil 1990). This setback is, however, primarily a product of political policy, rather than a failure of alcohol technology.

Alcohol fuels are not new by any means. Farm-produced fuel alcohol was extensively used in Europe between 1900 and 1920, and in North America early Ford Model T's came with a dual fuel alcohol/gasoline system as standard equipment. During the 1930's, a network of over 2000 service stations in the American midwest sold neat or blended ethanol fuels; in England the Cleveland Discol company successfully marketed high performance summer-grade alcohol fuels until the Second World War. Curiously, Cleveland Discol was a subsidiary of Standard Oil, which fought the introduction of alcohol fuels in North America while promoting them overseas. The post WW2 advent of cheap oil from the middle east, coupled with oil industry lobbying and improved gasoline refining technology eventually halted fuel alcohol use in the major industrialized nations (Bernton et al. 1982).

The reasons for renewed interest in alcohol fuels correspond roughly to the problems associated with petroleum based gasoline. First, methanol and ethanol burn very cleanly and completely. Menrad et al. (1988) found that levels of the three most common pollutants, carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NO_x) were much lower with methanol (and ethanol) than with gasoline. Emissions of another pollutant, formaldehyde (HCHO), are a problem when cold starting; the same study found formaldehyde levels from a catalyst-equipped engine to be approximately 6.5 times greater when cold than when warm. However, tests of warm catalyst-equipped methanol engines showed formaldehyde levels to be virtually the same as those from warm gasoline engines with catalytic converters. The actual levels found were:

	METHANOL	GASOLINE
NO_x	0.50 g/km	1.17 g/km
CO	0.60 g/km	1.90 g/km
HC	0.15 g/km	0.20 g/km
HCHO (cold)	9.25 mg/km	1.56 mg/km
HCHO (warm)	1.44 mg/km	1.56 mg/km

Other tests by the same authors show that control of transient throttle response during warm-up can minimize formaldehyde production, with or without a catalyst. A wide open throttle produced a 55% reduction in aldehyde emission compared to that found with a partially open throttle (128 ppm vs 232 ppm).

Two more reasons for interest in alcohol fuel is that it can be produced relatively inexpensively using both renewable and non-renewable resources, and from a wide variety of sources. Renewable resource production adds no net CO_2 to the atmosphere, an important environmental factor.

Ethanol is primarily produced by distillation, and many different crops can be used as feedstock, although yields differ. Wheat, for example, is a poor ethanol crop, yielding only 817 litres/hectare/year. (1 hectare [ha] = 2.5 acres). Corn averages 2200 litres/hectare/year, cassava 2160 l/ha/yr, and sweet sorghum 3610 l/ha/yr. Brazil extracts 6064 l/ha/yr from sugar cane, using two crops per year, and the cane waste, called bagasse, is burned to provide all needed process heat. An experimental farm at Palm Beach Junior College, Florida found that ordinary cattails, grown on marshy ground, yield an astounding 9475 l/ha/yr (Kovarik 1982).

Ethanol production is quite practical on a small to medium scale, making it a possible agricultural fuel for farmers with excess corn, grain, sorghum, or other crops (Agriculture 1980; Clark et al. 1971). Put into the perspective of a typical farm, a standard 160 acre quarter section, 64 hectares, will yield 140,800 litres (29,700 Imperial gallons) of 100% ethanol per year if farmed in corn, or 52,300 litres (11,000 Imperial gallons) if planted in wheat. The by-products of distillation, still high in protein, can be used as animal feed, or in the case of corn, be pressed for oil. The Province of Saskatchewan now offers a $0.40/litre subsidy to encourage building distilleries for producing ethanol fuel from surplus grains (Pederson 1991). New processes being developed by the National Research Council of Canada and others produce ethanol directly from the action of genetically tailored enzymes (Heath 1989; Kovarik 1982; Houghton-Alico 1982).

Methanol is produced today by catalytic oxidation of natural gas (CH_4), a process which is approximately 65% efficient and costs less than $0.13 per litre. Over 170 billion cubic metres of natural gas is now flared at the wellhead annually because transportation is too costly or difficult. But wellhead flare gas catalytically converted to methanol is much easier to store and transport, so wellhead conversion of this waste energy is one of the main sources of methanol envisioned for the near term, in addition to existing natural gas wells. Saudi Arabia has already completed one of the world's largest projects to use previously-flared natural gas; one of the main products is methanol (Kovarik 1982).

But methanol can also be produced from any material that will decompose into hydrogen and carbon monoxide, or into hydrogen and carbon dioxide. It can be manufactured for $0.08 to $0.12 per litre by gasification of coal, of which the world has huge reserves (McElroy 1982). Gray and Alson (1989) suggest that high sulfur coal could be used exclusively for methanol production, with low sulfur coal going to power plants and manufacturing, thus reducing acid rain. More importantly for long term supply (and for the environment), methanol can be produced from many types of biomass, especially wood, woody plants, weeds, and grasses, all of which are high in cellulose. Since many of these plants grow rapidly without cultivation and in poor or marginal soil, they would not divert land use from agriculture. Another possible feedstock is wood and paper waste, much of which is now incinerated or landfilled. Methanol from this dry biomass costs $0.13 to $0.16 per litre, and can be manufactured either by partial combustion with oxygen (producing CO & H_2O, then CO_2 & H_2), or by pyrolysis (destructive distillation) of material into CO and H_2. Partial combustion is now the favoured method; pyrolysis is less efficient and more difficult. The process gas from either method is passed over a copper-zinc-aluminum catalyst at 250 °C and 5000 kPa, yielding methanol. Experiments are also underway to find a successful enzymatic process to turn woody biomass (which is mainly cellulose) directly into methanol (Thring 1983; Kovarik 1982).

Wet biomass, including animal and human wastes, can also be used to make methanol. Union Carbide has developed the Purox process, which involves catalytic conversion of methane obtained from digesters. Cost is $0.13 to $0.25 per litre (Thring 1983). One of the major long term advantages of renewable resource methanol production is that it, like ethanol production, is closed with respect to the carbon cycle. It would, therefore, be a zero net contributor of the greenhouse gas CO_2 to the atmosphere. Assured supply is also a factor in favour of renewable resource production, but with a worldwide abundance of coal and natural gas this is not seen as a major consideration in the near term.

Methanol's cleanliness, ease of production, and diversity of sources of supply all combine to make it a very attractive fuel. The final argument for choosing methanol over ethanol, at least in North America, is that it avoids the "food vs fuel" debate. Whether produced from natural gas, coal, wastes, or biomass, methanol production does not divert agricultural resources. Ethanol, on the other hand, requires a choice of whether to use crops (wheat, corn, etc.) for human consumption or for fuel production. In some cases, as is happening now in Saskatchewan, crop surpluses make this choice a non-issue at the local level, and fuel ethanol production is encouraged. On a global scale, though, this aspect of methanol technology is seen by many governments to be an important consideration for the future, especially when over half of the world's population lives at or below the subsistence level (Kovarik 1982; Houghton-Alico 1982).

1.2 METHANOL FUEL COLD STARTING TECHNIQUES

Methanol, then, is gradually emerging as the fuel of choice for alcohol fuel research programs in North America. Many technological aspects of using ethanol and methanol as fuel are similar, so much of the research is transferable in any case. Research in transportation applications is concentrating in several areas, including emissions control, corrosion prevention, lubrication improvements, fuel additives, engine efficiency, and cold starting. Cold starting is, at present, one of the major stumbling blocks to widespread use of alcohol fuels, especially in areas like Scandinavia, northern Europe, the northern U.S., and Canada.

The cold starting problem is that for all practical purposes, in an ordinary spark ignition (SI) engine, neither methanol or ethanol will vapourize in concentrations high enough to allow starts at temperatures below +10 degrees Celsius (Jorgensen 1988; Gardiner et al. 1990a). The cause of this, simply stated, is low vapour pressure. Even at 21 °C, the vapour pressure of methanol is only 13 kPa (as compared with 60 kPa for gasoline), and it drops rapidly with decreasing temperature. Even a very rich mixture, and thus a higher equivalence ratio, does not improve cold starting very much. Gasoline, being a blend of many different hydrocarbon molecules, has a higher vapour pressure and will boil over a range of temperatures from 35 °C to 200 °C (Thring 1983). Even at sub-zero temperatures, partial vapourization makes some ignitable gasoline vapour available, since the lighter, more volatile molecular fractions vapourize first. Not so with methanol. Unlike "wide cut" gasoline, methanol is a single component fuel, containing only one type of molecule. This molecule has a high boiling point, 64.6 °C, and a high latent heat of vapourization, 1101.1 kJ/kg (Bolz & Tuve 1973). Figures for ethanol are similar.

There are, of course, a number of possible solutions to this problem. One is to use an auxiliary gasoline system, as is done on neat ethanol (E100) cars in Brazil (Pischinger et al. 1982), and as has been experimented with by others including Laveskog et al. (1988) and Moncrieff et al. (1988). These systems require a small auxiliary gasoline tank, plus the associated equipment to switch between alcohol and gasoline. A cold engine is started normally on ordinary gasoline, and then switched to alcohol when warm. There is no question that auxiliary gasoline starting systems work, but the added cost, complexity, and driver inconvenience make them a less than ideal solution. There are also political issues to be considered; a dual-fuel vehicle might be unacceptable for environmental and regulatory reasons, even if it operated satisfactorily. Menrad et al. (1988) and others have shown that an engine completely optimized for methanol does not have good operating or emission characteristics when running on gasoline; likewise, an engine adjusted to operate satisfactorily on both fuels exhibits poorer efficiency, economy, and emissions than when optimized for one fuel or the other.

Another cold starting solution is to blend methanol fuel at the refinery with some other substance, like gasoline, that has good vapour pressure characteristics at low temperatures. Various combinations, ranging from 10% methanol/90% gasoline (M10) to 85% methanol/15% gasoline (M85), are being researched. M85 does have some cold starting difficulties, but they are nowhere near as severe as 100% or neat methanol (Gardiner et al. 1990b).

Iwai et al. (1988) reported that in blended methanol fuels at sub-zero temperatures, the vapour component was almost entirely gasoline, even when using very high percentages of methanol. There are, however, other considerations with combinations like M85, including luminosity, toxicity, flammability, and phase separation. Also, at the present time M85 and M100 are two competing strategies for implementing methanol as a primary transportation fuel.

If neat methanol is the fuel of choice, and if an auxiliary starting system using a more volatile fuel is rejected, how is a methanol fuelled, spark ignitioned (SI) engine to be started, especially at sub-zero temperatures? Are there improvements to engine calibration and equipment which will make the startability of a neat methanol SI engine acceptable? Several different solutions to these questions are now under investigation. At the outset, it is important to distinguish between compression ignition (CI) engines and spark ignition engines (SI), and also between direct injection (DI) and homogenous charge (HC) carbureted or port fuel injected engines. The majority of automobile engines used today are spark ignited (SI) and homogenous charge (HC), while most heavy trucks and buses use Diesels, or CI-DI engines.

CI-DI engines have already been successfully redesigned for methanol fuel. Although methanol has a high octane number (106), and so resists autoignition (knock) quite well, it has a relatively low cetane number. The cetane rating of methanol is typically 0.5, compared for 45 for #2 Diesel fuel. This means that injection timing must be adjusted, and in many cases some form of ignition assist is also used. Projects at Ford (LoRusso and Cikanek 1988), Caterpillar (Kroeger 1986; Richards 1986), Detroit Diesel Allison (Toepel et al. 1983; Jaye et al. 1988) and elsewhere (Johns et al. 1988; Tsunemoto et al. 1988) have all met with considerable success. Road testing of a Detroit Diesel Allison methanol CI-DI engine is now taking place in Edmonton (Loyie 1991); other, more extensive tests have been in progress for some time (Wuebben et al. 1990; Unnasch et al. 1990; King & Bol 1988). Cold starting assists like glow plugs, auxiliary spark plugs, and manifold heating give these engines a limited cold starting capability comparable to existing Diesel engines. Consideration must be given, however, to the fact that many engines used in heavy transportation are rarely shut down, as is the case with long-haul trucks, or are garaged when not in use, like city buses. For this reason, sub-zero cold starting is not quite the same problem as it is for an automobile using an SI-HC engine.

At least one SI-DI engine has been researched: the United Parcel Service (UPS) Direct Injection Stratified Charge (DISC) engine. This multi-fuel design combines a high (13:1) compression ratio (CR) and direct fuel injection system with the Texaco Controlled Combustion System (TCCS). The TCCS utilizes a high energy pulsed 4000 Hz AC ignition, special multi-electrode spark plugs, and a stratified charge combustion chamber. UPS began independent development of this engine in 1978 so that their fleet of over 40,000 parcel delivery vans would have flexible fuel capability if shortages of one type of fuel were to occur. Development and testing continued throughout the 1980's, with 500 vehicles eventually being fitted with the 4.8 litre limited production test engine (Lewis et al. 1980; 1983). In 1987, Siewert and Groff reported that this engine had achieved unassisted cold starts to -29 °C in less than three seconds at cranking speeds of 110 rpm or higher on neat methanol fuel. This is the lowest temperature for sub-zero methanol fuelled engine starting reported anywhere. Ironically, the DISC engine project was halted in 1990; although it has excellent cold-starting characteristics, its emission levels, particularly hydrocarbon and unburned fuel emissions, are so high that current North American vehicle emission standards make it unusable (Gardiner 1991).

The cold-starting success of the DISC engine is largely due to the combination of a finely atomizing direct injection system and a stratified charge combustion chamber which creates a combustible mixture in the vicinity of the spark plug. A small part of this dense local mist of fine droplets is then vapourized and ignited by repeated strikes of the 4000 Hz AC 3-gap ignitor. Compression heating was initially thought to be the mechanism for droplets vapourizing. However, Jorgensen (1988), studying compression temperatures in the UPS engine, showed conclusively that compression heating could not vapourize even 10-20 micron methanol droplets when the ambient (intake) air was at normal room temperature, let alone at -29 °C. A critical factor in compression heating is engine displacement, because heat losses and cylinder blowby are much greater problems in a smaller engine. Tests (Scholten et al. 1984) of an 11.4 litre Mercedes Diesel engine with a CR of 12.5:1 showed a peak compression temperature of 300 °C, while Jorgensen found peak temperatures of less than 150 °C. Further experiments by Jorgensen showed that droplet vapourization in the UPS engine was most likely the result of spark heating of droplets in very close proximity to the electrode gap. Repeated strikes would first vapourize and then ignite an alcohol droplet, and the flame would then propagate through the surrounding cloud of methanol droplets. This type of droplet heating mechanism appears to also explain results obtained in experiments detailed in the following chapters, and will be discussed later.

Although the sub-zero starting performance (and the multi-fuel operating performance) of the DISC engine is excellent, its poor exhaust emissions characteristics have caused it to be shelved indefinitely. Even if the emissions problem could be solved by optimizing for a single clean burning fuel, there are other problems. The DISC engine is large, moderately heavy, and quite expensive to build and maintain. (For that matter, any system involving direct cylinder injection is much more expensive than is carburetion or port injection). One of the DISC's main features is the patented TCCS technology, so the price of every unit built includes a royalty to Texaco. It is possible that the 4.8 litre DISC can be scaled down to an engine in the 1.5 to 2.5 litre range, suitable for passenger car use, but only if the emissions problem can be overcome. That development is far in the future, as things now stand.

Modification of or addition to homogenous charge SI engines for M100 operation is the most prevalent area of M100 passenger car engine research at the present time. It is also, in terms of sub-zero starting, an area with indifferent results to date. Although good M100 operating characteristics have been achieved for ambient temperatures above +15 °C and/or warm engines, the sub-zero starting ability of HC-SI engines is much less promising. Cold starting techniques being researched break down into the following areas: Recalibrated engines; In-cylinder techniques; Electric vapourizers; Fuel-fired heaters and vapourizers; Catalytic gaseous fuel generators. All of these techniques have so far shown inferior cold starting performance to that of gasoline engines (which start to about -30 °C), and it may be that only a combination of techniques will eventually solve the problem. A brief review of the various techniques is thus in order, outlining the limits as they currently exist.

Catalytic gaseous fuel generators use the principle of breaking down the methanol fuel into a volatile and ignitable gas, such as dimethyl ether (DME). Ament (1990), reporting on an SAE student competition, notes that a device using a microwave magnetron fuel heater and an alumina-ceramic catalyst to generate DME was used with M85 fuel at +4 °C. This was the coldest temperature available; the system might well have gone lower. A temperature of +4 °C is not exceptional -- starts with M85 have been reported to -29 °C -- but the scheme might yield better results in future tests (Dasch et al. 1991). Gardiner et al. (1990a) mention unpublished results reported to them in which a device generating hydrogen and carbon monoxide allowed starts at -20 °C; the device apparently burns methanol in a "flaming glow plug" to provide heat to a catalytic cracking element, which is sprayed with methanol. A 40 second warm-up time is quoted, but starting times were not. Problems with these systems may include complexity, electrical consumption, and the generation of enough gas to allow driveaway as well as starting. It may be that this approach will be coupled with some other enhancement to overcome this problem.

Fuel fired heaters are used to heat fuel, intake air, or both. They are bulky, slow, expensive, and complicated. Because of the relatively large masses to be heated with some types, they can also consume large amounts of fuel. Lastly, fuel vapourized by such a heater is likely to re-condense when it enters the cold cylinder (since it is almost impossible to heat the whole engine), so the future of these devices is not promising (Gardiner et al. 1990a).

Electric vapourizers, as the name implies, use battery driven resistance heating to vapourize enough methanol fuel for starting. A typical device was that of Laveskog et al. (1988), who reported starts down to -8 °C using a 1 kw heater to vapourize 150-200 ml/minute of methanol. The device was operated for 90 seconds, and starting was accomplished with 5 seconds of cranking immediately thereafter. One disadvantage to this unit was that it required the installation of two heavy-duty batteries in their Saab test car, since heater operation rendered a single battery incapable of turning the starting motor. A second problem was that driveaway "had to be done in an extremely gentle way as the maximum amount of vapourized methanol that could be fed continuously was only about 75 ml/min."

Recalibrated engines are those whose characteristics have been adjusted to give the best possible results with methanol fuels. Techniques typically include richened mixtures and increased compression. High (>12:1) compression ratios are desirable in any case in a methanol engine, in order to take advantage of the increased efficiency and power made possible by methanol's high octane rating. Increasing compression also improves compression heating effects, although these effects in cold starting are likely to be less in small displacement engines, as noted earlier. Extremely rich mixtures have been reported to improve cold starting from +15 °C down to about °0 C, although cranking periods of up to 120 seconds were used. This method is also produces high levels of formaldehyde emission. Since the vapour pressure of cold methanol is low, one explanation offered for this phenomena is that the accumulation of liquid fuel in the cylinders gradually improves engine compression enough to allow starting, and also gradually increases the number of fuel droplets being "thrown around." This explanation also agrees with the observations of several researchers regarding time to "first fire." In many cases, even with extremely rich equivalence ratios, several tens of seconds are often required before any ignition is observed, let alone engine start (Iwai 1988; Gardiner et al. 1987; 1990a).

A new study by Gardiner et al. (1991) reports that an engine using a camshaft modified to give prompt exhaust gas recirculation (Prompt EGR) achieved starting at only 0 P°C. However, this technique brought the starting limit of the engine down to the firing limit of the ignition system. The authors suggest that Prompt EGR, coupled with an improved ignitor, may be capable of better results.

The best recorded cold starting performance on M100 for a recalibrated but otherwise unaided SI-HC engine is that reported by Iwai et al. (1988), where a homogenous charge SI engine was started at -6.5 °C on M100 fuel. The engine used in this test was a port injected 1.8 litre 4 cylinder unit having a 12:1 compression ratio, and was said to be able to start and run within 60 seconds. Cranking speed was quite high -- 200 rpm -- and this may have been a factor in their good results. However, the same study reported that a similar port fuel injected engine would only start down to +3 °C, and a carbureted version would only start down to +1 °C.

In-cylinder engine modifications include techniques to give improved fuel atomization within the cylinder, increased cranking speeds (which were also used by Iwai et al.), and improved ignition methods. High cranking speeds were tested by Gardiner and Bardon in 1986, and some improvement in startability did result on their 2 cylinder test engine as rpm was increased. At 200 rpm cranking speed the engine could be started at +6 °C; at 400 rpm it could be started at -4 °C; and at 600 rpm the lowest starting temperature was -5 °C. It should be noted that "cranking speed variations were negligible in the tests . . . as the laboratory cranking apparatus used an electric motor one third as powerful as the test engine." On the other hand, the engine used had compression characteristics somewhat worse than an automobile engine, with a CR of only 6:1. (Gardiner et al. 1990a).

Cold starting tests of the UPS DISC engine also found a definite relationship between cranking speed and the time to first firing, with a minimum cranking speed of 110 rpm for reliable starting of that engine (Siewert & Groff 1987). [For comparison, the elderly 4 cylinder 2000 cc engine used in the experiments described in the following chapters had cranking speeds of 98 to 78 rpm at 0 °C to -20 °C and only 630-660 kPa of compression, although the design CR was 9.5:1 (1130-1330 kPa). The characteristics of this engine are thus clearly inferior to those of the engines used by most other researchers, while the results are superior].

Poor fuel atomization, which prevents the formation of an ignitable cloud of fuel droplets close to the ignition source, is the feature of the SI-HC engine that prevents good cold starting on neat methanol. The opposite properties, of course, are at the heart of the extraordinary cold starting performance of the UPS DISC engine, which delivers an extremely fine fuel spray directly into an electric arc. Modifications to try and duplicate the DISC effect in an SI-HC engine aim specifically at creating a dense uniform cloud of finely atomized fuel droplets around the spark plug. The problem with this approach is that it is exactly contrary to the way the engine is designed to operate; it seems "impossible to implement this process with any engine limited to out-of-cylinder fuel delivery" because all of the fuel must be in the cylinder before ignition is started (Gardiner et al. 1990a).

1.3 PLASMA JET IGNITION AS A METHANOL COLD STARTING AID

Tests of enhanced and alternative ignition systems have to date shown no change from standard ignition systems, which deliver only about 30 millijoules to the spark plug being fired (Obert 1973). Blair (1988) reported no improvement in EPA tests of systems using high energy and/or high voltage, as well as a 10 kV AC arc. This result was partially confirmed by experiments described in Chapter Three, in which energies up to 10 Joules used with a conventional spark plug produced a minimal improvement in the ability to ignite cold alcohol, or to start an engine at even moderately cool temperatures. The main reason for this lack of success is that there is only a small chance that an alcohol droplet will be in the correct location -- very close to the spark gap -- when the discharge is fired. Unless the droplet is at the right distance, there is also little chance that it will be both vapourized and ignited, even if the discharge contains enough energy to do so. There is even less chance that a homogenous cloud of fuel droplets will exist near the spark plug and so be ignited by the small flame kernel resulting from the lighting of a single droplet (Jorgensen 1988).

The plasma jet ignitor (PJI), which expels a short duration, turbulent, high energy puff of hot plasma, creating multiple flame kernels in a surrounding cold mixture, would seem to offer at least a partial solution to this problem. The ability of the plasma jet to ignite a variety of mixture conditions is well documented (Topham et al. 1975; Cetegen et al. 1980), and the mechanism and effects of turbulent mixing and entrainment of surrounding gas have been studied in some detail. Turbulent entrainment, a higher initial flame speed, and more complete combustion are known to result from the formation of turbulence and multiple flame kernels (Smy et al. 1987; Cavolowsky et al. 1987; Szelewicki 1990). Maly (1980) demonstrated that spark sources with very short durations exhibit greatly increased efficiency in transferring electrical energy from the source into thermal energy in a target gas. Given that one of the main problems of cold starting a methanol fuelled HC-SI engine is vapourizing and lighting droplets that may not be located right at the ignition source, the mixture penetration, turbulent mixing, and turbulent heat transfer characteristics of the plasma jet would seem to offer a clear advantage over a gap-type ignitor. A plasma puff could entrain alcohol droplets through turbulent mixing, and the larger flame front that results from the plasma puff would have more chance of reaching other droplets. Another advantage to the PJI is that it deposits a much greater amount of energy in the combustion chamber in a short time. As mentioned earlier, Jorgensen (1988) found that compression heating did not contribute in any meaningful way to the ignition process in the UPS engine (with a 13:1 compression ratio) and that spark heating was the only mechanism that would account for their successful results. Although the PJI delivers only a single pulse, compared with the multiple strikes of the 4000 Hz UPS ignition, a plasma puff carries a great deal of energy and allows better transfer of this energy than does a gap-type discharge. Thus, the plasma jet seems, on initial inspection, to have several advantages over conventional ignitors for a methanol fuelled SI-HC engine application.

A thorough literature search revealed no report of any attempt to use the plasma jet ignitor as an aid to starting of a methanol fuelled vehicle, although numerous studies of the plasma jet ignitor as used in engines running on gasoline were found (many cited in Dale & Oppenheim 1981). Experiments at the University of Alberta using the PJI to assist Diesel engine cold starting were successful at temperatures down to -55 °C (Wilson 1985; Dale et al. 1985). A comprehensive review of 77 published and unpublished results of cold starting experiments using neat methanol by Gardiner et al. (1990a) explicitly states that there are "no published reports of attempts to use plasma jets for methanol cold starting." Therefore, the experiments described in the following chapters, which used plasma jet ignitors for lighting cold methanol and for sub-zero starting of a methanol fuelled automobile, probably do not duplicate any techniques or results described in the published literature to date.

This thesis consists of five chapters. Chapter Two, entitled Experimental Apparatus, discusses the equipment and components used in each experiment. Chapter Three, Experimental Studies, details and presents the results of three separate studies using the plasma jet to ignite cold methanol. The first was a simple test to show whether or not a plasma jet would light cold alcohol when a J-gap plug would not, and showed that a correlation existed between ambient temperature and energy required for ignition. Another measurement with the same setup determined the optimum "reach" of the plasma jet when igniting cold alcohol (i.e., the maximum ignitor-to-alcohol distance which allowed ignition). Plug wetting was found to be a factor in this experiment, with a wet plug producing a larger and more luminous plume. The occurrence of this type of plug wetting in an engine was later confirmed by communications with other researchers (Gardiner 1991).

The second study, also carried out at atmospheric pressure, involved the use of a cooled low pressure automobile fuel injector to deliver a charge of cold alcohol droplets into a chamber containing turbulent cold air. The object was a more exact determination of the relationship between ambient temperature and ignition energy. Temperatures used in this experiment were from -5 °C to -24 °C. Since plug wetting (or its absence) was thought to be a factor in the ignition process, a method of making it more uniform from shot to shot was developed, This took the form of a PJI with a sintered bronzed end cap, described in Section 2.2. Although the energy levels required by this ignitor were the same as those for a standard PJI, its operation in this experiment was more consistent. The fuel injector provided a repeatable, measured charge of relatively large droplets, such as might be found in a homogenous charge SI engine. Fuel was not sprayed directly onto the ignitor, but rather was directed past it, using the distance determined in the first experiment. The plug was wetted by the edge of the fuel cloud, but variations in wetting were decreased by the wick action of the sintered end of the ignitor. A delay was incorporated between the injector trigger and the plasma jet trigger so that the fuel charge was delivered before the plasma jet was fired. When minimum energy vs temperature curves for the plasma jet had been obtained, some of the measurements were repeated using the same energies and temperatures with a J-gap ignitor. It was discovered that not only would the J-gap not cause ignition under the same conditions as would the plasma plug, it would not cause ignition even with much higher energies and when sprayed directly with fuel, to the limits of the test setup.

The final study was a sub-zero car starting test of a PJI system installed in a 1973 4 cylinder Volvo sedan whose fuel system had been converted and readjusted for alcohol. Standard PJI ignitors without sintered ends were used. The engine was not otherwise recalibrated, and so this was less than an optimum test. Starts were tried at ambient temperatures ranging from 0 °C to -28 °C at energies up to 15 Joules, and results were recorded on a go/no-go basis. Comparison tests using standard spark plugs with both normal and high ignition energies were also conducted to provide a base line against which the plasma jet ignition performance could be measured. Driveaway tests were not conducted, since the vehicle transmission was inoperative in cold weather and because vehicle movements were restricted by power cords. A definite energy vs temperature curve was obtained, and the lower temperature limit at which starts were obtained appeared to result from equipment limits and oil stiffness, rather than from a failure of the plasma jet ignition mechanism.

Chapter Four is a general discussion of the experimental results, problems, calculations, and questions arising from the data. Also mentioned are some possible avenues for further examination and development suggested by the experiments performed. Chapter Five is a summary chapter, containing the conclusions of the thesis. Appendix One contains the results of an erosion test in which a PJI was fired 37.5 million times (75 million discharges) using the all-high-voltage supply described in Section 2.4. This number of shots equates to about 40,000 km of operation in a 4-cylinder engine. Erosion was found to be considerably reduced compared to that encountered with the type of power supply described in Section 2.3.

CHAPTER 2: EXPERIMENTAL APPARATUS

2.1 PLASMA JET IGNITOR

The plasma jet ignitor, or PJI (figure 2.1) used in these experiments consists of a 1.55 mm diameter tungsten electrode mounted in a ceramic tube whose bore is 1.6 mm. The 9.65 mm o.d. tube is mounted with Swage-Lock fittings into a threaded casing similar in style to that of a conventional automobile spark plug. However, the plasma jet ignitor casing differs from a spark plug in that it is capped with an orifice plate having a 1.5 mm hole coaxial to the centre of the tungsten electrode. Rather than protruding from the plug, as does the electrode of a conventional spark plug, the electrode is recessed 4 mm into the ceramic tube. A 4 mm x 1.55 mm cavity is thus created in the plug, giving a volume of 7.55 mm^3.

The performance characteristics of a plasma jet ignitor are determined, to a large extent, by the construction and dimensions of the cavity within the plug (Grant et al 1983; Weinberg 1986). By selecting larger diameters of tungsten electrodes, the cavity diameter -- and thus the cavity and initial plasma volume -- can be increased. Likewise, increasing or decreasing the distance that the tungsten electrode is recessed into the plug also changes the cavity volume. However, the allowable setback

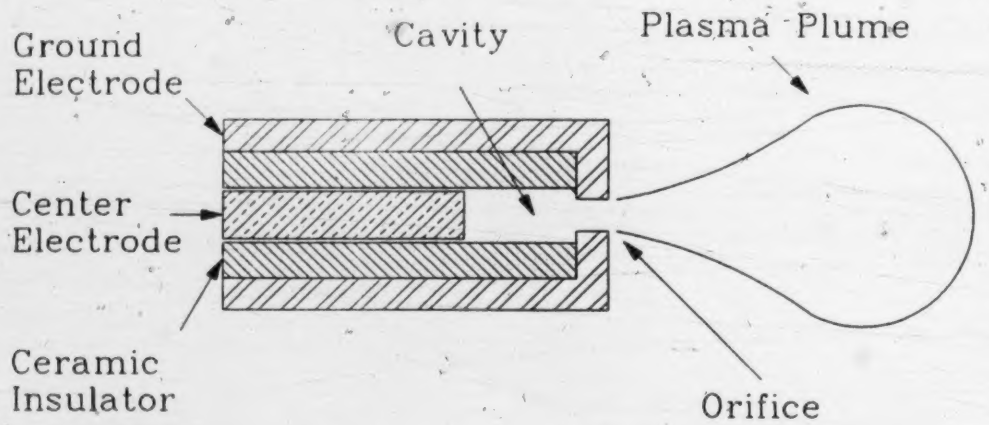

Ground Electrode
Cavity
Plasma Plume
Center Electrode
Ceramic Insulator
Orifice

Figure 2.1 Plasma Jet Ignitor

distance is affected by other considerations, mainly electrical in nature. If the distance of the electrode from the plate is too great, electrical breakdown will not occur, since the insulation factor of the gap is more than the firing voltage can bridge. By the same token, a gap that is too short will allow a premature breakdown of the gap and result in a lower energy discharge. The optimum separation of the electrode from the plate is a distance that is just within the outer limit of electrical breakdown.

Another factor that affects the performance of the plasma jet ignitor is the orifice size. Varying the orifice diameter effectively changes the mass flow rate with which the plasma is expelled. Altering the diameter can thus cause the puff to be either sonic or supersonic when expelled (Cavolowsky et al. 1987), which in turn affects plume penetration into the combustible mixture. If, however, the orifice is too small in relation to the cavity volume, the expulsion of the plasma plume from the cavity and subsequent ignition will be impeded. Since the hot plasma is viscous, relative to the gas it was made from, viscous flow through a small orifice makes it impossible for the cavity pressure to drive a large enough plume quickly enough to ignite the mixture.

The actual overall efficiency with which a plasma jet ignitor converts electrical energy into thermal energy in the form of a plume of hot plasma ($T \approx 10^4$ K) (Topham et al. 1975) is approximately 10%, although the actual efficiency from shot to shot varies by up to 100% from this figure, depending on operating conditions. Most of this variation in efficiency occurs in the transfer of stored energy from the power supply capacitors to the igniter; the transformation of electrical energy to heat energy within the ignitor is relatively constant -- about 25% (Smy et al. 1983). A certain amount of scatter is therefore inherent in any experiment using the PJI, even if identical energy settings are used for every shot fired.

In internal combustion engine applications, a unique problem encountered with decreasing orifice size is oil fouling. Although the hot plasma exhibits considerable pressure within the cavity, a droplet of oil can effectively seal off the cavity and foul the plug. Two styles of PJI have been tried to overcome this problem: choked orifice and straight-through orifice. Choked orifice ignitors are those in which the orifice diameter is smaller than the cavity diameter, while in a straight-through ignitor, the two dimensions are the same. Experiments by Ostergaard and Haley (1989) have shown the straight-through ignitor to be much better in avoiding the oil fouling problems, and these were used throughout.

At rest, the plasma plug cavity is filled with whatever mixture surrounds it, whether flammable or non-flammable. In the case of sub-zero temperature ignition of methanol, the main component filling the PJI cavity would be air, since the methanol does not vapourize to any significant degree at low temperature, and since there is no mechanism by which droplets of methanol enter the cavity proper. Even if a bare PJI was wetted by methanol droplets, as was frequently observed, they rarely entered the cavity and shorted out the ignitor. This gives the PJI another advantage over a J-gap ignitor; when a J-gap is wetted with methanol droplets, it frequently shorts out and quits operating (Blair 1988; Dasch et al. 1991).

When a high energy discharge occurs between the centre electrode and the orifice plate, the resulting high temperature ($\approx 10^4$ K) and pressure within the cavity causes dissociation of the reactant molecules into ions and electrons (Topham et al. 1975). This dense cloud of dissociated material is called a plasma, and is neutrally charged overall. As the temperature (and thus the pressure) rises inside the cavity, a jet or plume of hot plasma is expelled into the outside environment through the orifice, with jet exhaust velocities on the order of 5×10^3 m/s (Smy et al. 1987). Turbulent eddies are created along the sides of the expelled plasma plume as the result of friction between the boundary layer of the plasma plume (approximately 1 mm) and the surrounding cold, dense flammable mixture. Eddies are also created as the plume exits the orifice plate. The turbulence thus created is known as electrically induced turbulence (Haley et al 1989), and it has a number of effects on the ignition process. One of the main ones is improved mixing and combustion of air and fuel, since the result of turbulence is that "ambient mixture is brought thereby into intimate contact with the hot reactive core of the jet," enhancing combustion (Cavolowsky et al 1987). When operating within an engine, this also helps create a more homogenous mixture around the ignitor, allowing more complete and even combustion, and thus fewer and less toxic emissions and by-products.

In the case of low temperature ignition of methanol fuel, electrically induced turbulence almost certainly causes the entrainment of small amounts of the surrounding methanol mist into the plasma plume. Also, when the orifice plate is coated by a film of methanol, a small amount of this fuel will be picked up by the plume exiting the orifice and entrained. This entrained methanol is then heated, vapourized, and ignited by the hot plasma plume. When this occurs, plume length and luminosity are increased. There is also a noticeable increase in the loudness and sharpness of the sound of the ignitor firing.

A final advantage of the plasma jet ignitor is that it creates a much larger flame kernel at the instant of ignition than is possible with a conventional surface gap or J-gap ignitor (Szelewicki 1990), which aids the initiation of combustion because of its larger surface area. Not only is this flame kernel larger, but it is more reactive; the turbulent structure within the plasma jet transports radical ions into the reactive region of the flame kernel to enhance combustion (Smy et al. 1987).

2.2 ENHANCED PLASMA JET IGNITER

From the beginning of the experiments it was observed that once the PJI orifice plate had been coated with cold methanol fuel, the luminosity and length of the plasma plume was increased substantially. A much louder report was also heard, indicating more energy. Although a film of fuel on an ignitor is a normal consequence of cranking an engine (Gardiner 1991), it was more difficult to reproduce in an experimental setup, and varied from shot to shot. This had the effect of introducing another variable into the measurement of energy vs temperature, particularly in the injector experiment described in Section 2.6. In an attempt to introduce some consistency to the process of plug wetting, a method was sought by which methanol could be introduced into the immediate vicinity of the orifice when the plug was fired. The first thought was to somehow deposit a very small metered amount of cold methanol into the PJI cavity just as the discharge was triggered, similar to the methods proposed by Orrin et al. (1981) and Weinberg (1986). This approach was abandoned because of the cost and complexity involved, and the method finally used was to fit a thin (1.5 mm) end piece of sintered bronze over the existing orifice plate of a PJI. This sintered bronze disc, originally a high pressure regulator filter from a SCUBA breathing apparatus, was attached using a high temperature epoxy, then line-bored through the existing orifice to the same diameter as the existing orifice. The idea was that the sintered material would act as a "wick" for the cold methanol. A fairly constant amount of methanol would then be entrained into each plasma plume as it was expelled from the orifice, eliminating variations and allowing a more consistent measurement of energy.

The initial test of the enhanced PJI showed a considerable improvement in consistency when lighting both pools of cold methanol and mixtures of cold methanol mist and cold air, although the energy requirement did not change from that of a standard PJI. Both types of plugs were fired dry and then their orifice plates were wetted manually with a methanol film from a hypodermic syringe. In both cases plume length (as measured visually) went, (at an energy of 4 Joules) from an average of 1.2 cm (unwetted) to 3.1 cm (wetted), and luminosity and loudness increased similarly in both ignitors. Both styles of plug were then tested without any manual wetting in the injector chamber described in Section 2.6, and the enhanced PJI was more consistent in plume length and luminosity from shot to shot. The enhanced plug was thus used for all subsequent injector chamber experiments, in order to reduce variations from plug wetting. If the injector system had been set up so that the ignitor was more evenly wetted, or even sprayed directly, the enhanced PJI would probably have been redundant. However, since it was desired to observe the interaction of the fuel charge and the plume without disturbance caused by the body of the ignitor, the enhanced plug was used.

An attempt was made to test this system on the ignitors used in the Volvo test car, to see if starting was improved in any material way. Unfortunately, the attempt failed when the epoxy used to fasten the sintered bronze discs to the existing PJI plugs melted. In any event, energy vs temperature measurements for the Volvo engine, using un-enhanced plugs, were similar to those for the injector experiment, using an enhanced plug. This tends to follows the findings of the initial test of the enhanced vs normal PJI, where the plume length and luminosity of both were similar when wetted.

2.3 AC POWER SUPPLY

The power supply (figure 2.2) used as the primary energy source for all three experiments is a dual stage design. Stage one is a high voltage, low energy supply which emulates a standard automotive coil-type ignition system, supplying a 30 kV pulse with an energy of approximately 30 millijoules. This high voltage pulse provides the initial breakdown path for a high energy release through the three-electrode gap. The high energy section is a variable (0-1380) voltage, high current system whose energy is stored in capacitors ranging from 2 to 32 microfarads.

In stage one, the 120 VAC line voltage is stepped up and then rectified to approximately 400 volts DC. The rectifier output charges a 2 microfarad 600 volt oil-filled capacitor, which is also in series with one side of the primary of an ACCEL model 140305 automobile ignition coil. The other side of the coil primary is grounded. The system is triggered by applying a positive 5 volt pulse to the primary of an 11Z12 pulse transformer, one side of whose secondary is connected to the gate of an 2N5171 Silicon Controlled Rectifier (SCR). The other side of the pulse transformer secondary is grounded, as is the cathode of the thyristor. When the gating pulse is applied, the anode of the SCR, connected to the positive terminal of the charged 2 microfarad capacitor, is grounded via the SCR cathode.

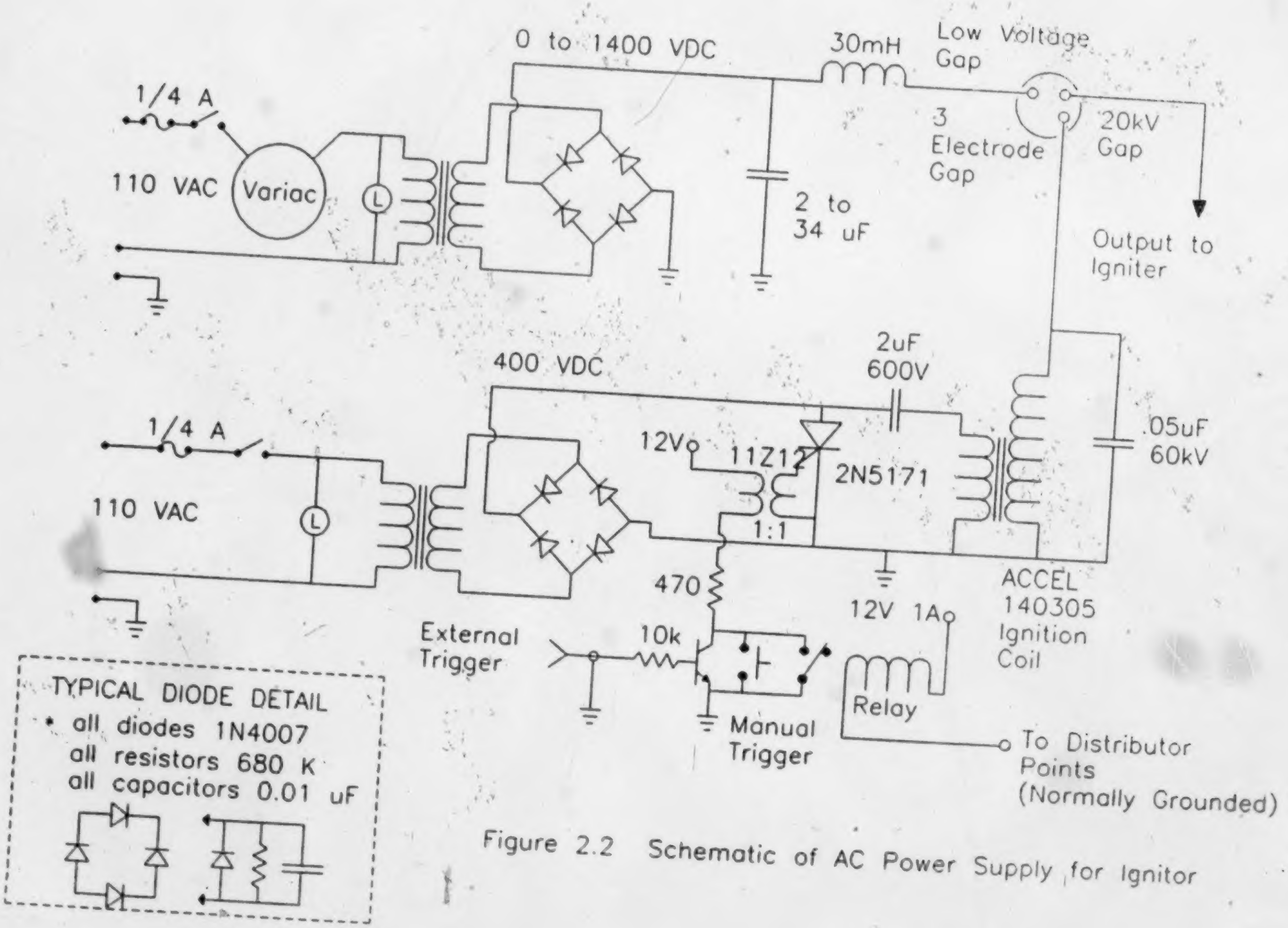

1/4 A
110 VAC
Variac
L
0 to 1400 VDC
30mH
Low Voltage Gap
3 Electrode Gap
20kV Gap
2 to 34 uF
Output to Igniter
1/4 A
110 VAC
L
400 VDC
12V
11Z12
1:1
2N5171
2uF 600V
.05uF 60kV
470
10k
External Trigger
Manual Trigger
12V 1A
Relay
ACCEL 140305 Ignition Coil
To Distributor Points (Normally Grounded)
TYPICAL DIODE DETAIL
• all diodes 1N4007
all resistors 680 K
all capacitors 0.01 uF

Figure 2.2 Schematic of AC Power Supply for Ignitor

This completes the discharge path of the capacitor, and it dumps its stored energy through the primary of the ignition coil.

The coil then steps up this 400 volt pulse to a pulse which rises to the 30,000 volts needed to break down the path in both the three electrode gap and the plasma jet cavity. As the voltage rises, energy is stored by charging a 0.05 microfarad, 60 kV capacitor, paralleled with the coil secondary. When the breakdown voltage is reached, the stored energy is suddenly discharged through the high voltage section of the three electrode gap and into the plasma jet.

In stage two, the power section, a Variac autotransformer in the 120 VAC primary controls the stepped-up output of the transformer secondary, which is then rectified in a diode bridge. The output voltage ranges from 0 to 1380 volts DC, although for practical purposes voltages below 400 volts DC are not useful. This DC voltage then charges a 2 microfarad 2000 volt oil-filled storage capacitor through a 500 ohm current limiting resistor, providing an energy of 1.88 Joules at 1380 volts. Additional external capacitors with values of 1, 2, 4, 8, 16, and 32 microfarads were added to increase the energy storage capacity as needed. One side of the capacitor is grounded; the other, hot, side is connected to the third electrode of the three electrode gap through a 30 millihenry air core inductor. This inductor blocks the 30 kV trigger pulse from the capacitor and diodes of the high energy side, which are not rated for this voltage.

When the trigger section of the power supply is fired, the spark jumps the first and second electrodes of the three electrode gap, and in so doing raises the potential of the second, or output electrode. This rise in potential causes breakdown between the second and third electrodes. Energy stored in the power capacitor is thus dumped through the ionized gap and passed on to the plasma jet ignitor, where the gap within the cavity has also broken down. As soon as the energy in the capacitor has been exhausted, the ionized path vanishes and allows the power capacitor (and the trigger) to recharge for another shot.

2.4 12 VOLT MOBILE POWER SUPPLY

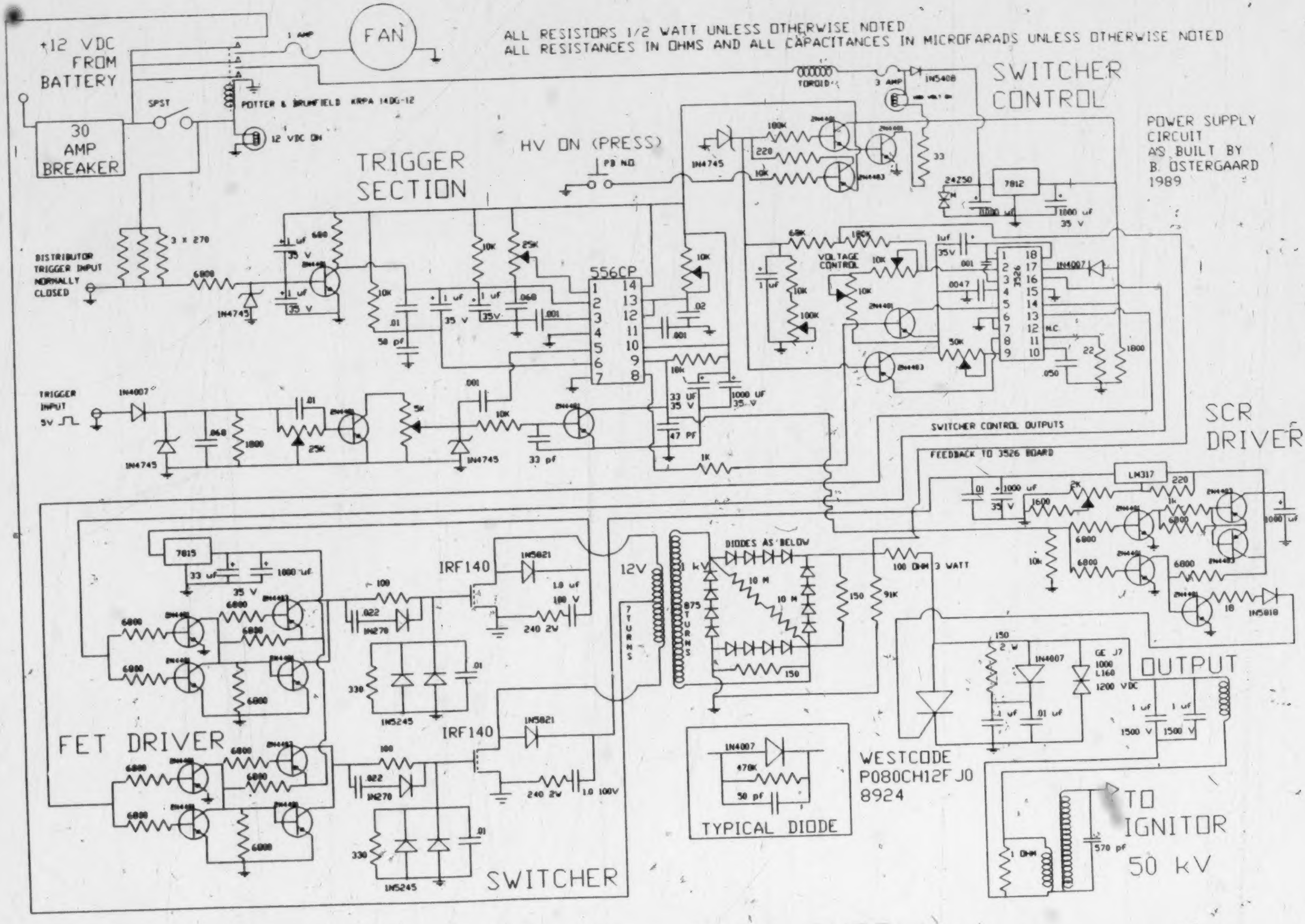
Previous research into the development of pulsed plasma jet ignitors has shown erosion of the cavity and orifice to be a major problem, especially in continuous operation (Smy et al. 1983, 1985). Erosion of this type is related not to the total energy of the discharge, but rather to the number of Coulombs of charge passing through the system. Smy et al. found that between 20 and 25 micrograms per Coulomb were eroded from a hardened steel orifice using a stored energy of 8 Joules at 700 volts; rates of 30 to 40 micrograms per Coulomb were recorded for mild steels. However, Smy et al. (1985) and experimental results described in Appendix 1 show that erosion is dramatically reduced by using a much higher voltage at the same energy level. In tests of the system described below, using 1 Joule at 20,000+ volts, approximately 37 million shots were needed to produce serious erosion effects.

The most common type of PJI power supply is the two stage type, as discussed in Section 2.3. In this supply, the initial gap breakdown is accomplished by a short duration, low energy (30 mJ) spark of about 30,000 volts potential (similar to an ordinary automobile ignition system); the breakdown thus created allows the discharge of a high energy low voltage (1000 volts is typical) supply through the same ionized path. A typical 1 Joule discharge at 1000 volts may, in a 10 microsecond pulse, require the passage of 0.001 Coulombs of charge (I=100 amps). Thus, it may be seen that for experiments involving large numbers of discharges, the standard PJI supply is a major source of ignitor degradation.

One way of overcoming this difficulty is to increase the discharge voltage used on the plasma jet ignitor while maintaining the same energy input. Increasing the voltage to 20,000 volts means that for a 1 Joule, 10 microsecond discharge, only 5 x 10^{-5} Coulombs of charge are put through the plug (I=5 amps) -- a vast improvement, as initial test results show.

The possibility of vehicular operation required a supply that would operate on a 12 VDC source; likewise, the characteristics of road testing made a high firing rate mandatory. A typical 4 cylinder engine turns at between 3000 and 4000 rpm at 110 kmh road speed (without overdrive), which translates to a maximum firing rate of 67 Hz for the power supply. Some reserve over this figure was, of course, desirable, so a maximum repetition rate of 100 Hz was set as a design target.

With a maximum repetition rate of 100 Hz, and a maximum discharge energy of about 1 Joule, a power supply capable of supplying and switching 200 watts was designed (figure 2.3). The first stage is a switching-type DC-to-DC converter plus its controls; this ups the 12 VDC to approximately 1000 VDC in one step. The rest of the circuit consists of two coupled resonant L-C tank circuits. The output capacitor (2x1 uf, 1500 V) is charged to 1000 volts by the DC switching supply and then held at constant voltage until discharged by the triggering of the SCR. The signal used for the SCR trigger also turns off the DC-to-DC converter, so that the SCR is not held open once this capacitor has cycled. Energy is coupled through the 1:40 transformer, and charges the 570 pf capacitor. Before the peak (40,000 volts) voltage is reached here, breakdown begins within the plasma plug orifice, releasing the stored energy via a high frequency resonant discharge.


ALL RESISTORS 1/2 WATT UNLESS OTHERWISE NOTED
ALL RESISTANCES IN OHMS AND ALL CAPACITANCES IN MICROFARADS UNLESS OTHERWISE NOTED

POWER SUPPLY
CIRCUIT
AS BUILT BY
B. OSTERGAARD
1989

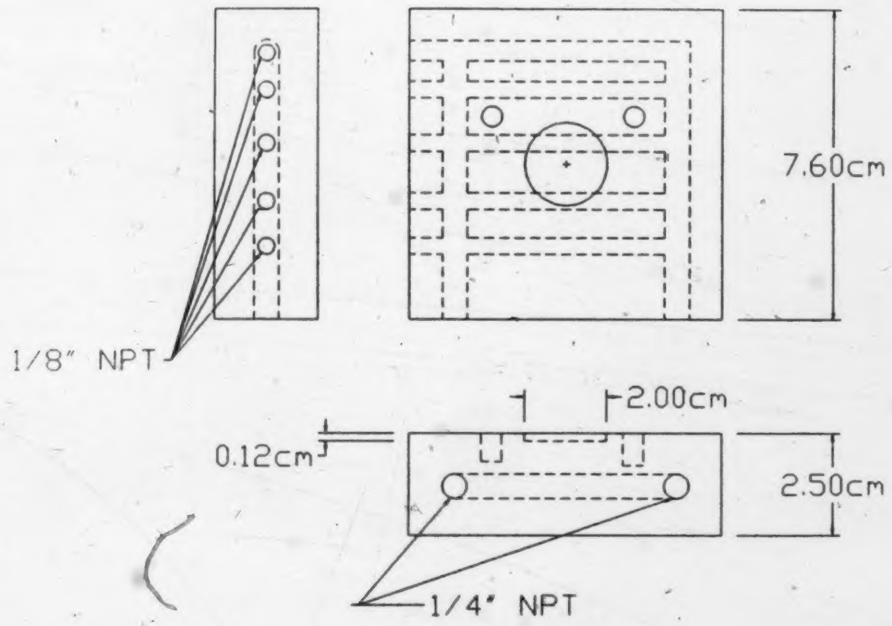
+12 VDC FROM BATTERY
30 AMP BREAKER
SPST
1 AMP
FAN
POTTER & BRUMFIELD KRPA 14DG-12
12 VDC ON
TRIGGER SECTION
HV ON (PRESS)
PB NO
DISTRIBUTOR TRIGGER INPUT NORMALLY CLOSED
3 x 270
6800
680
1N4745
1 uf 35 V
10K
25K
.01
50 pf
.068
.001
556CP
1 2 3 4 5 6 7
14 13 12 11 10 9 8
.02
33 UF 35 V
1000 UF 35 V
47 PF
1K
TRIGGER INPUT 5V
1N4007
1800
5K
33 pf
TOROID
3 AMP
1N5408
SWITCHER CONTROL
100K
220
33
24250
7812
1000 uf 35 V
68K
VOLTAGE CONTROL
3526
1 2 3 4 5 6 7 8 9
18 17 16 15 14 13 12 11 10
N.C.
.0047
50K
22
.050
2N4401
2N4403
SWITCHER CONTROL OUTPUTS
FEEDBACK TO 3526 BOARD
SCR DRIVER
LM317
1600
2K
1k
6800
10k
18
1N5818
7815
33 uf
35 V
1000 uf
IRF140
100
.022
1N270
1N5821
1.0 uf 100 V
240 2W
330
1N5245
FET DRIVER
SWITCHER
12V
7 TURNS
1 kV
875 TURNS
DIODES AS BELOW
10 M
150
100 OHM 3 WATT
91K
1N4007
470K
50 pf
TYPICAL DIODE
WESTCODE P080CH12FJ0 8924
150 2 W
.01 uf
GE J7 1000 L160 1200 VDC
OUTPUT
1 uf 1500 V
1 OHM
570 pf
TO IGNITOR 50 kV

FIGURE 2.3 12 VDC POWER SUPPLY

Energy not coupled into the plasma jet then flies back, partially recharging C1. At this point, the SCR latches open once again, the DC-to-DC supply is turned back on, and C1 is then recharged to await the next trigger impulse.

2.5 METHANOL POOL EXPERIMENT

As an initial proof of concept, an experiment to test for any correlation between temperature and ignition energy was devised. In this experiment, the object was to cool a small (0.1 ml) pool of methanol and its surrounding air to a specified temperature and then attempt to ignite it, noting the minimum energy required at that temperature. Ignition was determined visually, since methanol burns with a characteristic blue flame clearly visible in a darkened room. Mallinckrodt Analytical Reagent Grade anhydrous methanol (99.9% methanol by volume) was used for this experiment. A milled aluminum block (7.5 cm x 7.5 cm x 2.5 cm) was constructed, with 6 internal coolant galleries and a small circular "dish" (24 mm x 0.5 mm) on the upper face (figure 2.4, 2.4a). This block was placed within a 40 cm x 20 cm x 10 cm (8 litre) rectangular Lucite enclosure into which cooled air could be piped after it was closed (figure 2.5). A Fisher # 15035 laboratory grade thermometer (-100 °C to + 50 °C) and a thermistor were fitted into holes in the surface of the block near the dished area.


7.60cm
1/8" NPT
2.00cm
0.12cm
2.50cm
1/4" NPT

COOLED ALUMINUM BLOCK

FIGURE 2.4

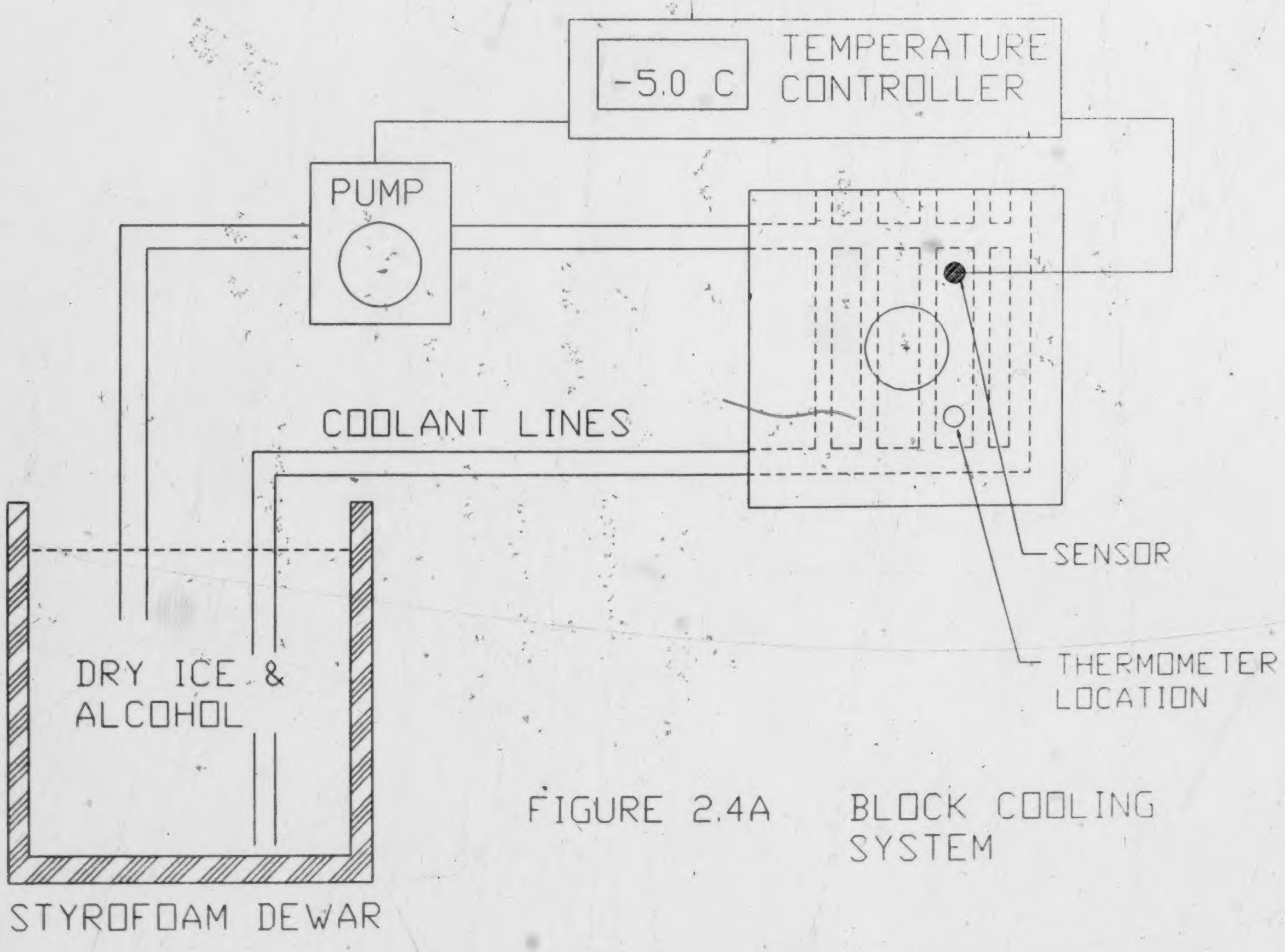

-5.0 C
TEMPERATURE CONTROLLER
PUMP
COOLANT LINES
SENSOR
THERMOMETER LOCATION
DRY ICE & ALCOHOL
STYROFOAM DEWAR

FIGURE 2.4A BLOCK COOLING SYSTEM

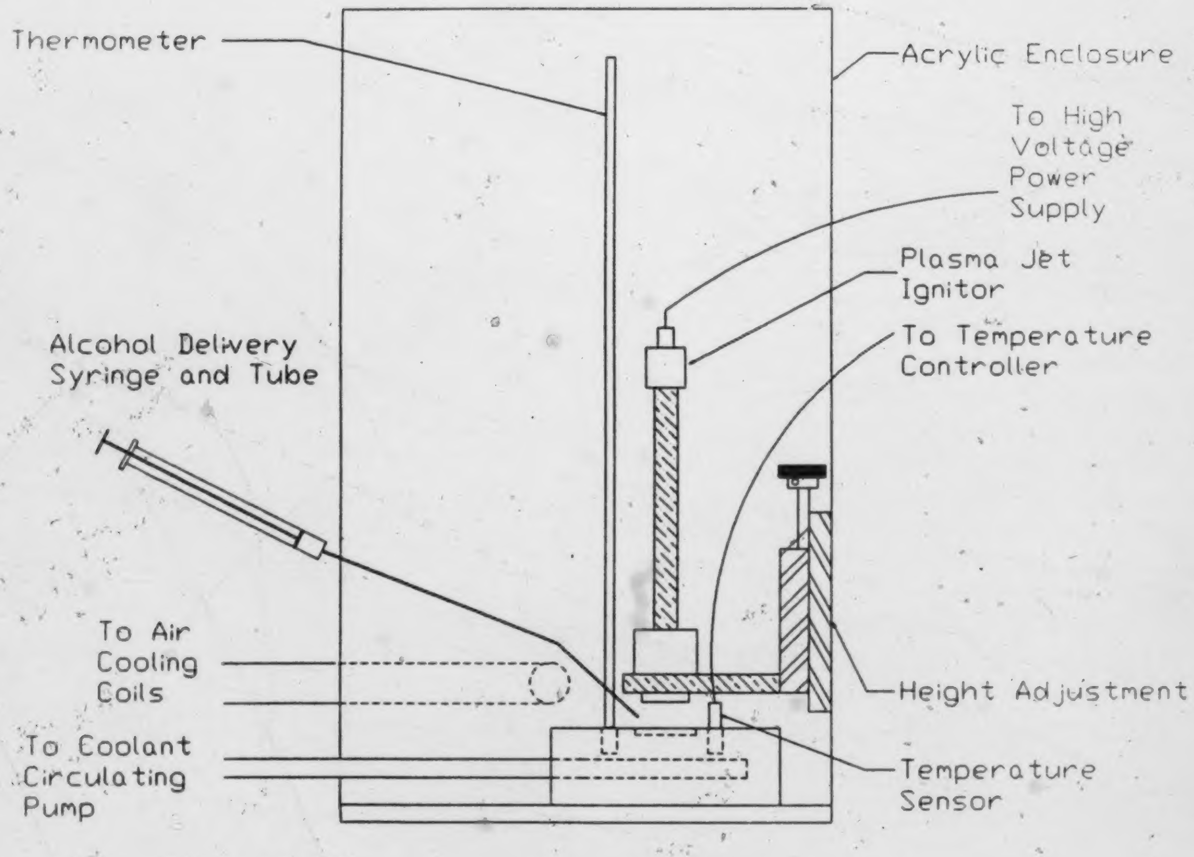

Thermometer
Acrylic Enclosure
To High Voltage Power Supply
Plasma Jet Ignitor
To Temperature Controller
Alcohol Delivery Syringe and Tube
To Air Cooling Coils
Height Adjustment
To Coolant Circulating Pump
Temperature Sensor

Figure 2.5 COOLED BLOCK SETUP

The thermistor used was the sensing element for a temperature control circuit (based on a commercially available temperature sensing module, Radio Shack # 277-123) which ran the coolant pump and heating element. Another thermometer of the same type was suspended 6 cm above the block to read ambient air temperature.

The ignitor under test was mounted on a height-adjustment screw mechanism, and the distance above the block could be read to the nearest 0.5 mm. Connections for the ignitor were fed through the chamber walls, as were coolant hoses and a brass methanol delivery tube attached to a calibrated syringe.

Cold air was provided by passing dry compressed air through a cooling coil (submerged in a bath of dry ice and alcohol) and then piping it through a short insulated line into the experiment chamber. The outlet air temperature could be varied by adjusting the pressure, and thus the flow rate. A flow rate of 3 litres per minute produced an outlet air temperature of approximately -12 °C in the chamber. To allow temperature equalization, air was allowed to flow for 3 minutes before each shot, with the rate adjusted to allow the desired temperature to be reached.

After two minutes of air bleed, the block cooling system was switched on and allowed to cool to the desired preset temperature. Alcohol coolant was used, drawn from a reservoir of alcohol and dry ice. The block generally reached its operating temperature in a few seconds, with the coolant pump automatically cutting out at a temperature slightly above that desired, to allow for thermal conductivity between the cooling galleries and the block. With the chamber air and the cooled block both at the desired temperature, a metered (0.10 ml) amount of methanol was placed in the circular depression and allowed 90 seconds to come to thermal equilibrium with the cold block and the surrounding cold air. Air and block temperatures and power supply energy were recorded, the ignitor was fired, and the result (ignition or non-ignition) was recorded from visual observations. The room where the experiments were done was darkened throughout.

If the pool did not ignite, it was mopped up using a long handled swab passed through a fitting in the side of the chamber, then fresh methanol was added and allowed to cool for 90 seconds. The energy level was then increased, and the ignitor fired again. If the pool of methanol did ignite, the surface of the block was swabbed clean (small amounts of water condensed from combustion products in many cases), fresh cold air was vented into the chamber, and the cycle begun again.

2.6 METHANOL INJECTOR EXPERIMENT

This experiment was intended to duplicate more closely some of the conditions that would be experienced when cold starting an automotive-type spark ignition engine using methanol fuel. It was assumed from numerous references in the literature that injection would be the preferred method of fuel delivery. Fuel injection, especially computer controlled fuel injection, allows much finer control of fuel delivery in relation to engine load and rpm, and thus allows better emission control and economy. The trend toward the use of computerized fuel injection can already be widely seen in today's automobiles. For a laboratory setup, a mist or spray of fuel would also be a more realistic test, since even in a carbureted fuel system, cold fuel enters the cold engine in a mist mixed with air. Finally, there is a direct correlation between fuel droplet size, evaporation characteristics, and ignitability; a small droplet is easier to ignite than is a large one (Jorgensen 1988).

Since the experiment was concerned with cold starting, it was required that the air, the methanol, and the ignitor be cooled to the temperature under test. A cold chamber 29 cm in diameter and 22 cm deep (14.53 litre) was constructed, and 10 cm ducts run from and to the outside through a centrifugal blower (figure 2.6). Since this series of tests was conducted during the period December

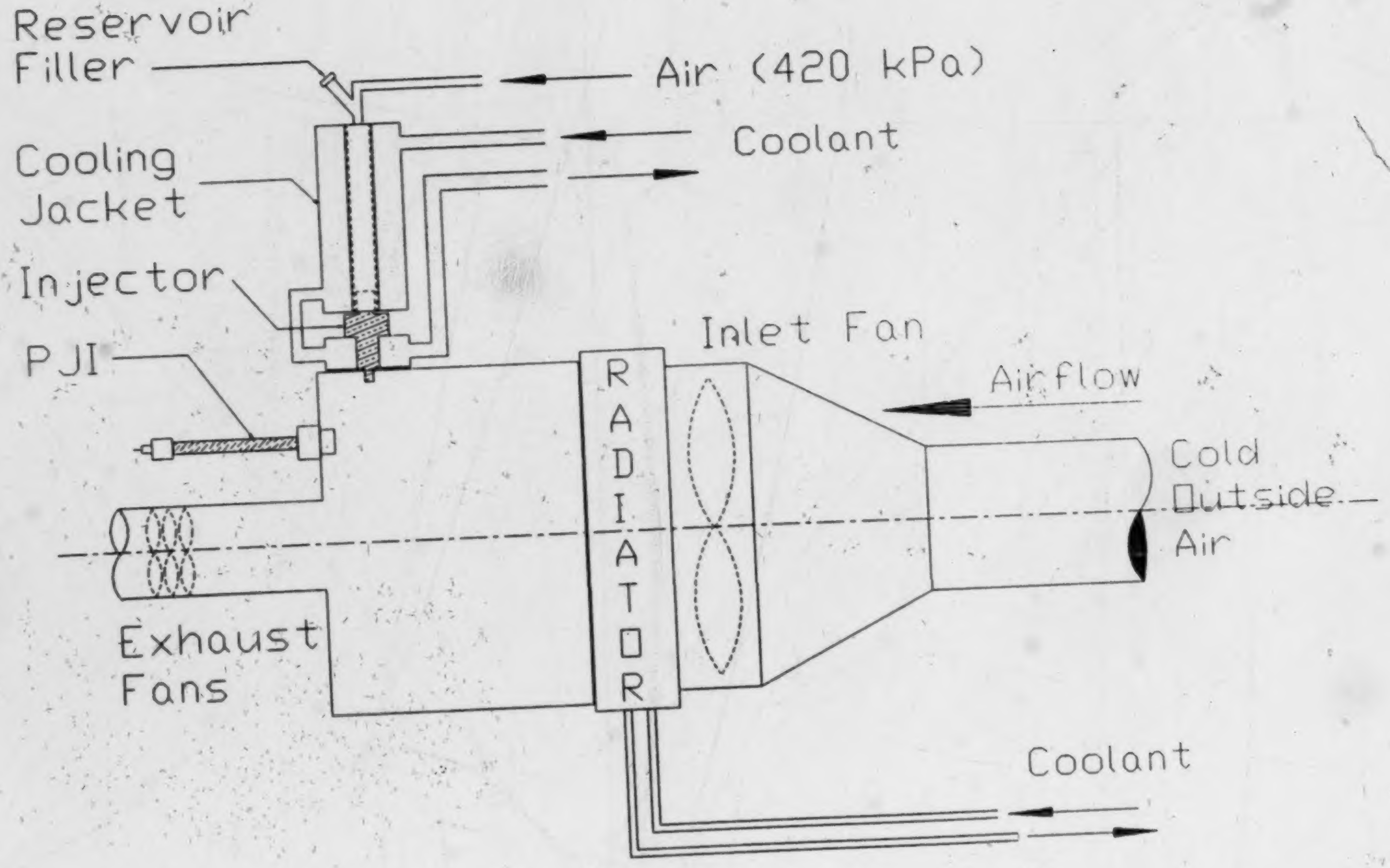

Reservoir
Filler
Air (420 kPa)
Coolant
Cooling
Jacket
Injector
PJI
Inlet Fan
Airflow
R
A
D
I
A
T
O
R
Cold
Outside
Air
Exhaust
Fans
Coolant

Figure 2.6 Injector Cold Chamber

1990 to March 1991, in the depths of a Canadian winter, it will be understood that the outside ambient air temperature, ranging between -5 °C and -45 °C, was always below zero. The system was insulated with 5 to 8 cm of foam to prevent its being heated by the surrounding room temperature air. Even so, the chamber air temperature was usually 5-6 °C warmer than the outside air. Therefore, a radiator with its own fan assembly was also placed in the ducting system ahead of the cold chamber. The liquid side of the radiator was connected to a Forma Scientific Refrigerated Bath/Circulator, whose coolant temperature was set at -33 °C. This allowed the incoming air to be cooled below the outside ambient temperature. A valve in the coolant line controlled the rate of circulation, and thus the additional temperature drop. Provisions were also made for the incoming and outgoing air ducts to be connected in a closed circuit system, to be used if the outside ambient temperature was too high to be useful. This system was used only once.

With both fans running, airspeed in the chamber was measured with a TSI Model 1650 Air Velocity Meter (hot film type), and was found to vary from 7.5 m/s at the outlet to 1.5 m/s at the chamber walls to 2.2 m/s directly in front of the radiator. In the area where the injector spray and plasma jet crossed, an air velocity of 4.2 m/s was observed. The flow in this area was quite turbulent, since the air stream was meeting a large circular flat plate with the 10 cm exit hole in the middle. Although it was not possible to characterize the turbulence with any degree of accuracy, tests with smoke trails and with the hot film anemometer clearly showed that airflow in the area of the ignitor was perturbed.

The fuel injection system used was an electrically driven low-pressure injector from a Chevrolet Lumina automobile engine. Triggering and pulse shaping was accomplished using a Motorola MC3484V2 Integrated Solenoid Driver chip. This device provided full positive injector opening and closing by initially delivering a high current pulse to the injector. After the initial pulse, current was reduced by a factor of 4, which was sufficient to hold the injector open while reducing electrical consumption and current heating in the solenoid (Motorola 1981).

A 30 ml methanol reservoir was mounted behind the injector and pressurized with air at 413.7 kPa (60 p.s.i.g.). The injector delivered 7.00 ml per 200 shots, an average volume of 0.035 ml per shot. This figure is in good agreement with the fuel consumption for a typical 4-cylinder engine (10 litres per 100 km @ 3000 rpm @ 100 kmh gives a consumption per stroke of 0.030 ml). Mallinckrodt Analytical Reagent Grade anhydrous methanol (99.9% methanol by volume) was used throughout. The injector and the reservoir were both enclosed in coolant jackets supplied from the circulating coolant bath. Coolant flow was controlled by a solenoid valve connected to the same temperature controller described in Section 2.5. The temperature sensing thermistor for the controller was clamped to the copper methanol reservoir just above the injector using GC Type Z9 Silicone Heat Sink Compound for good thermal conduction. The controller was calibrated by submerging a laboratory grade Fisher #15035 thermometer in the methanol reservoir, then cooling the assembly and plotting the relative readings of the thermistor and the thermometer. Thus, temperature readings from the thermistor could be corrected to the true methanol temperature inside the reservoir.

The injector and ignitor under test in the chamber were aligned so that the plasma plume and the spray plume from the injector were in the same plane, intersecting at approximately 90 degrees. The two components were mounted so that the spray met the plasma plume in mid-air, rather than having the injector spray an ignitor gap. Thus, only the plume expelled by the plasma jet ignitor protruded into the cloud of methanol droplets. As mentioned in Section 2.2, a plasma jet ignitor which had been modified to make plug wetting more consistent was used.

Both the injector and the ignitor power supply were triggered from a Wavetek model 187 Pulse/Function generator. A laboratory built delay unit inserted between the signal generator and the power supply trigger allowed the injector spray plume time to develop completely before the ignitor fired. The optimum delay was found to be 8 milliseconds, and was used for all experiments.

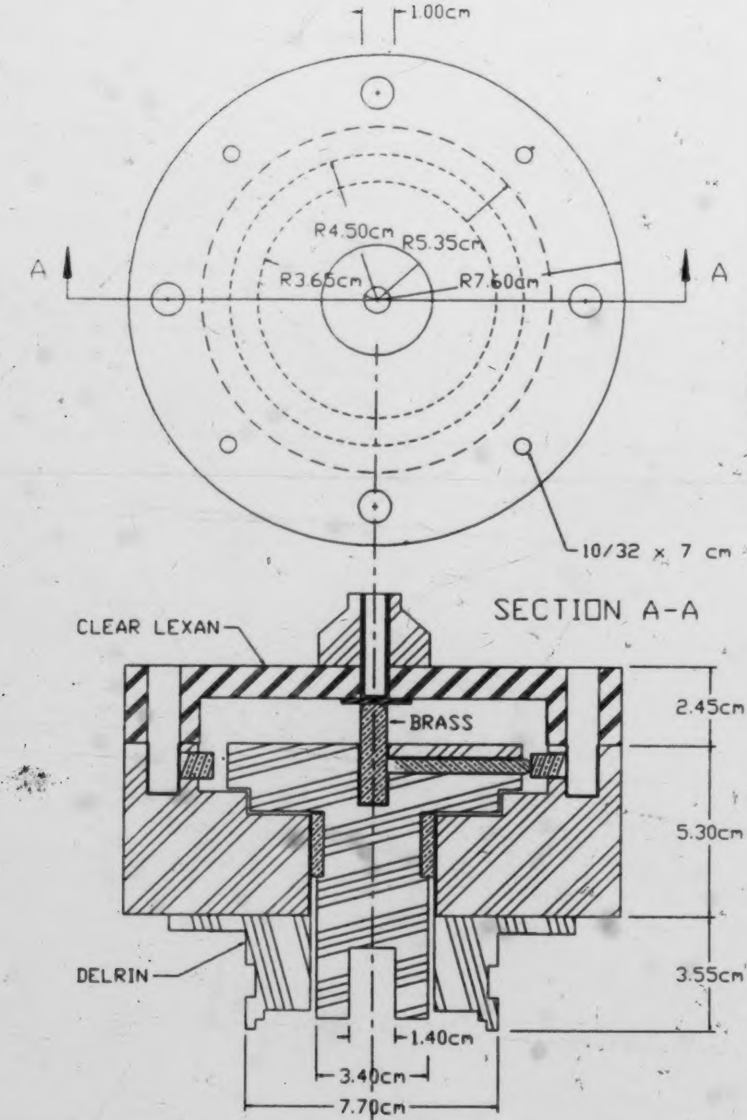
2.7 VOLVO IN-ENGINE EXPERIMENT

> "To mention the parts with which we had trouble . . . would take far too much time. Let it suffice to say that I do not recall any trouble with the dipstick."
>
> Charles Kettering,
> on a prototype railroad
> Diesel (Morgan 1972).

The final study in the series was an attempt to cold start a methanol fueled engine fitted with a high energy plasma jet ignitor system. Ordinary plasma jet ignitors, as described in Section 2.1, were used. In-engine testing is usually done on single- or multi- cylinder research engines in environmental chambers. However, since facilities for this were not available, an existing automobile was fitted with a methanol fuel system and plasma jet ignition, then tested for startability after cold soaking at ambient winter temperatures. Because of the vehicle used, this was something of a "worst-case" experiment. It was felt that if the system would work at all in a much less than ideal engine, it would certainly work on a newer and more mechanically sound engine. This would be especially true for an engine specifically designed in all respects for methanol operation, which included factors like a higher compression ratio (Pischinger et al 1982; Gardiner et al 1990a).

The test vehicle (Hobson's choice; it was left over from another experiment) was a Volvo 144 with a 4 cylinder, 2000 cc B20B engine. This vehicle, built in 1972, had over 189,000 km (118,000 miles) on the odometer when the experiment was started, and showed evidence of quite a bit of hard use. Cranking speed at -5 °C with a fully charged but cold battery was 78-80 rpm, down considerably from the factory specification of 200-250 rpm. The design compression ratio was 9.5:1; however, engine compression was only 633-666 kPa (95-100 p.s.i.g.) measured on a warm engine using a SNAP-ON compression tester. The engine oil was ESSO EXTRA 10W-30, which later proved an unfortunate choice; its high viscosity at low temperatures greatly restricted cranking speed. 0W or 5W would not only have allowed higher cranking speeds, but provided better lubrication.

The existing Volvo distributor was replaced with a much larger custom made unit (figure 2.7) which incorporated rubbing contacts, rather than the traditional air-gap. The larger body gave adequate dielectric spacing for the high voltage high energy discharges used, and the rubbing contacts reduced energy losses in the distributor. The Delrin body and rotor unit was grafted onto the lower


1.00cm
R4.50cm
R5.35cm
R3.65cm
R7.60cm
A
A
10/32 x 7 cm
SECTION A-A
CLEAR LEXAN
BRASS
DELRIN
2.45cm
5.30cm
3.55cm
1.40cm
3.40cm
7.70cm

VOLVO HIGH ENERGY DISTRIBUTOR

FIGURE 2.7

portion of a standard Volvo (Robert Bosch) JFUR4 distributor (in place of the cap and rotor), and the existing points were used to trigger the high energy power supply. Ignition timing was set at 28 °BTDC, the amount of advance which gave the best starting performance. This large ignition advance for methanol burning SI engines is consistent with that used by other researchers (Ament 1990; Babar et al 1990; Menrad et al 1988; Johns et al 1988).

The B20 engine used had twin SU sidedraft carburetors as standard equipment, and these were retained for the methanol test. Although a fuel injection system would have been preferable, it was not feasible to convert the engine for either direct or pre-chamber fuel injection.

To accommodate the methanol fuel needed, a one litre fuel tank was fitted to a 75 cm support on the front of the car. This height, found by experiment, ensured an adequate supply of fuel to the carburetors. Since the energy content of methanol is 19.94 MJ/kg (1.569 MJ/l), as compared to 43.670 MJ/kg (3.21 MJ/l) for gasoline (Siewert et al 1987), its stoichiometric air-fuel ratio is only 6.46. Thus, the required methanol fuel volume is almost double that of gasoline. This increased volume meant opening the carburetor jets to provide increased fuel flow.

A two-way fuel valve was inserted just ahead of the carburetors, with one side connected to the existing gasoline system and the other to the methanol fuel tank.

The valve was tested to ensure that there was no leakage of the fuel not in use, so that no gasoline would contaminate the methanol fuel supply and alter the results. No gasoline was observed to exit the valve when it was set for methanol or turned off, even under full pressure from the engine fuel pump. Thus, the cold-starting results seen were definitely for 100% neat methanol.

To adjust the carburetor, the engine was started normally on gasoline with the cold-start control on and allowed to warm to operating temperature, then switched over to methanol. As the methanol entered the system, the carburetor jets were opened until the engine ran normally, showing no signs of fuel starvation. The cold-start control, which set the throttle to fast idle and opened a secondary jet to supply extra fuel for starting, was left on. Other researchers have reported having to drill out the jets of single carburetor engines, but the needed mixture was just within adjustment range with two carburetors, since each carburetor was using an extra jet and had only two cylinders to supply. This adjustment was adequate for starting and running in neutral up to 1000-1200 rpm; it would probably not supply enough fuel for running under load. The mixture was then adjusted for an optimum carbon monoxide (CO) level using a Beckman Model 590 N.D.I.R. HC/CO exhaust gas analyzer. On gasoline, the best obtainable reading (taken previously with the same instrument) was 2.3% CO; on methanol the reading was 0.8%. Constant fluctuation was noted in the hydrocarbon (HC) reading when operating on methanol, and no definite reading was obtained. Researchers at Volkswagen of Brazil found that hydrocarbon data from alcohol burning engines was unreliable when measured with FID gasoline exhaust analysis equipment. N.D.I.R. equipment was not tested, and no information was available on its reliability for alcohol fuels. Regarding FID's, the Volkswagen researchers said:

> "the use of the FID [flame ionization detector] in emitted HC [hydrocarbon] measurement is erroneous, owing to the presence of unburned [alcohol] in the exhaust gases. Although they are not hydrocarbons, they cause a signal in the flame ionization detector, thus giving a false indication on the real HC amount contained in the exhaust gases (Joseph et al 1988)."

Fuel flow at idle (700-800 rpm) was measured for both gasoline and methanol. Methanol was used at 110 ml/min, or 6.6 litres per hour. In terms of fuel volume per cylinder per revolution, the consumption is 0.079 ml per power stroke, which is almost exactly twice the measured gasoline consumption of 55.7 ml/min or 0.040 ml/stroke for the same engine. This doubled consumption figure is entirely consistent with theoretical expectations, and also with the experiences of other researchers.

Once the carburetors had been re-calibrated for M100, the car was moved outside to its test location using the 12 VDC mobile supply and plasma jet ignitors. This location was exposed, so that warming effects of wind shadow or shelter would be minimized. No block heater or other heating device was, of course, used at any time. Once moved to its new location, the warm engine was run at fast idle on the plasma jet ignitor system and neat methanol for approximately one half hour. This purged any traces of gasoline from the fuel system, and allowed a final check of normal warm operation. Once this was done, only the methanol fuel system was used.

Starting tests were usually conducted twice daily, at least 12 hours apart, and the engine was not run more than 2 minutes after starting in order to minimize warm-up. Temperature readings of both ambient temperature and block temperature were initially taken using a laboratory thermometer for air temperature and a contact thermistor for block temperature. In every case these were found to be the same, within the limits of accuracy of the measuring devices. No throttle opening other than than set by the cold start control was used; in fact, the throttle and cold start control were not altered once initially set. One starting test was generally conducted in the morning, before sunrise, and another in the evening, after sunset.

The test procedure, detailed in Chapter Three, involved cranking in short intervals of 10 seconds on and 10 seconds off, with the energy level being delivered to the plasma jet ignitors being increased each time. Increments of about 100 volts were typically used, starting at 500 volts. This procedure, although not ideal, was adopted to try and minimize compression heating and other effects of long cranking periods noted earlier. If a start had not occurred after 60 seconds of cranking time (i.e., two minutes elapsed time), the attempt was deemed a failure. A successful start involved starting and idling for at least 60 seconds; as was mentioned in Section 1.3, a driveaway test was precluded by the experimental setup. Idling well is, of course, a relative term; the cold-weather operation of the unaltered Volvo on gasoline was rougher than is typically found with some types of Japanese and North American makes. As a subjective evaluation, the engine ran no worse on methanol than on gasoline, and possibly somewhat better. As might be expected, engine starting became more reluctant, and engine operation rougher, as the ambient temperature decreased. Idling at the lower temperature starting limit was very rough indeed, and the engine shook heavily as it ran.

Part of this problem may be the result of a flame being initiated, but then partially or completely quenching on the cold cylinder walls cylinder walls. Certainly, in the case of methanol, which has a lower heat content per unit volume of fuel, there would be less heat available to sustain the combustion process. If the flame were to contact a very cold surface like a cylinder wall, even after being successfully ignited by the PJI, the "bulk quenching" effect of the cold metal could halt the combustion process before it was well developed. Flame quenching in this situation has been observed with other fuels (Gardiner 1991), and so similar behaviour seems quite likely with methanol.

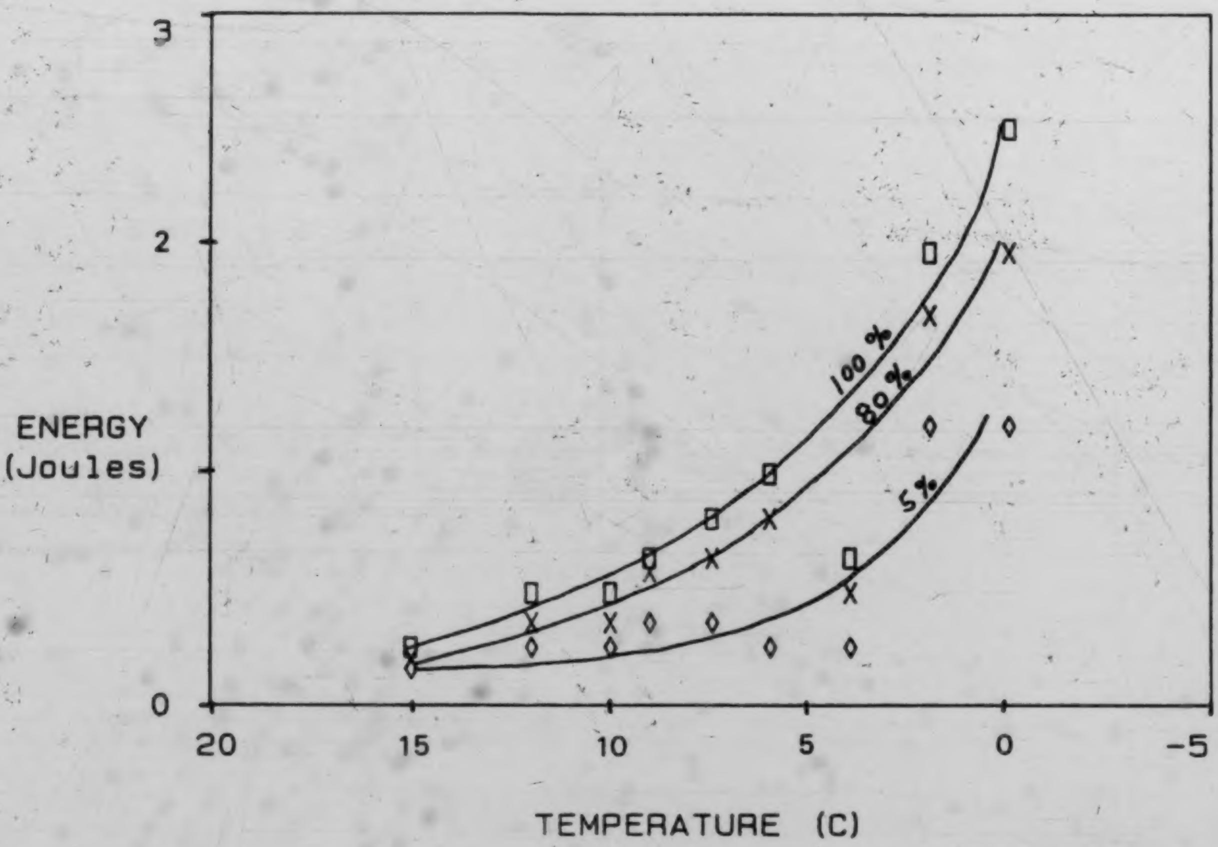
CHAPTER 3: EXPERIMENTAL STUDIES

3.1 COLD PLATE AND METHANOL POOL

In this initial experiment, the ability of the PJI to light a pool of cold methanol (and the amount of energy required) was tested, with temperatures beginning at +15 °C and decreasing. A pool of alcohol was chosen because it 1) simplified the number of variables acting in the situation, and 2) represented a worst case scenario, where alcohol coming into a cylinder would collect in a pool on top of a piston. This was, of course, a gross over-simplification of the actual cold starting environment in an engine, but it established a basis for further experiments.

The experiment was set up as described in Section 2.5, and temperatures from +15 °C to -10 °C were initially tested, with delivered energies from 0.5 to 5 Joules per shot. Results were impossible to obtain below 0 °C, owing to the blast effect of the plasma plume at higher energies. The experimental setup allowed only single shots, so that any heating effects from multiple firings or buildup of exhaust products from partial combustion would not be a factor.

Using this approach, the ability of the PJI to ignite cold methanol was confirmed, and a relationship between temperature and energy needed for ignition was established. Test results are summarized in figure 3.1; each point is



SINGLE SHOT IGNITION PROBABILITY
OF M100 POOL

FIGURE 3.1

the result of at least 10 trials at a given temperature and energy. The results showed that the chance of ignition occurring at a given temperature lessened as ignitor energy decreased; the curve of the overall energy required for a given lighting percentage rose sharply as temperature decreased. The scatter between the energy needed for a 100% lighting rate and the level at which ignition no longer occurred also increased, as did the percentage difference. At +15 °C the energy difference is from 0.25 to 0.16 Joules, or about 0.09 Joules; this is 36% of the energy required for a 100% lighting rate. At 0 °C the difference is from 2.45 to 1.21 Joules, or about 1.24 Joules; this is about 50% of the energy required for a 100% lighting rate. Some of the scatter in lighting ability vs energy is inherent in the energy transfer efficiency characteristics of the PJI. The actual overall efficiency with which a plasma jet ignitor converts electrical energy into thermal energy in the form of a plume of hot plasma ($T \approx 10^4$ K) (Topham et al. 1975) is approximately 10%, although the actual efficiency from shot to shot varies by up to 100% from this figure, depending on operating conditions. Most of this variation in efficiency occurs in the transfer of stored energy from the power supply capacitors to the igniter; the transformation efficiency of electrical energy to heat energy within the ignitor is relatively constant -- about 25% (Smy et al. 1983).

By varying the distance between pool and igniter at a fixed temperature and energy, an optimum distance range (3.0 mm, +/- 0.5 mm) was found. At shorter distances the methanol pool was dispersed by the plume blast wave without lighting, and at longer distances only the fringes of the plasma plume reached the methanol. Ideally, some of the alcohol would became entrained in the plasma plume, either by the face of the ignitor being wetted, or by droplets being entrained in the plume directly. This effect was clearly visible as a change in the color and increase in size of the outer part of the plasma plume.

A final part of the experiment was to substitute a J-gap spark plug for the PJI and test its lighting ability under the same temperature and energy conditions. The height between the J-gap and the pool was also reduced to improve the J-gap's chances. The outcome of this test was entirely negative; even with the plug sitting right at the pool's surface and using high energies, ignition only occurred above +10 °C, close to the +11 °C flashpoint of methanol.

3.2 COOLED METHANOL INJECTOR

This experiment sought to quantify more exactly the relationship between energy and temperature when using a PJI to ignite cold methanol, and to extend the temperature data to a lower limit, if possible. It was known from the experiments of other researchers with the DISC engine

(Siewert et al. 1988; Jorgensen 1988) that a fine spray of very cold methanol could be ignited if aimed directly at an 4000 Hz AC arc. It was also clear that ignition in the DISC engine did not occur unless a dense homogenous cloud of very small droplets existed in very close proximity to the spark gap, and unless a multiple-strike spark was used. In a homogenous charge engine, neither low nor high energy single and multiple strike systems produced ignition (Blair 1988).

Even in a cold HC engine, methanol atomized during the intake stroke can remain in droplet form during the subsequent compression stroke, although none of the droplets will vapourize much. What seems certain from past experiments is that few or none of these unvapourized droplets are ignited by the spark of a conventional J-gap ignitor. Even if the plug is wetted by droplets, ignition is unlikely to take place. If by chance one droplet is in the correct location, no adequate mechanism of droplet heating and flame propagation appears to operate.

The crux of the test was therefore to discover whether or not the PJI could do what a conventional spark plug could not: ignite cold methanol droplets in cold air. The primary area of interest was ignition (if it occurred) of the fuel charge by the plasma plume at different combinations of temperature and energy. A second area of interest was the interaction of the plasma plume with fuel droplets. To maintain even plug wetting without having the ignitor protrude into the fuel cloud produced by the injector, an enhanced plasma plug (described in Section 2.2) was used to eliminate variation from this source.

The test was conducted at atmospheric pressure, since the necessity of taking a large number of measurements (to overcome the wide shot-to-shot variation in PJI efficiency, discussed in Section 2.1) made operation within a pressurized bomb impractical. However, testing in this way introduced at least two divergences from actual in-engine practice, neither of which can be quantified. One of these would tend to improve the results as compared to an engine, and one would tend to worsen them. First, required energy measurement results would be somewhat improved at room pressure, since the PJI operation would not be altered by increased external pressure, particularly when using a "straight" or non-orifice plug (Ostergaard et al. 1989). As ambient pressure increases, the expelled plume length shortens; more energy is required to create a 1 cm plume at 6 atmospheres than at 1 atmosphere (Weinberg 1986). Second, since no compression heating would be present, the ambient temperature of the combustion air would be lower than it would be in an engine, which would then require somewhat more ignition energy. However, compression heating in cold-starting a small displacement engine may be less important than was previously thought (Jorgensen 1988).

After the experiment was set up and operating, test runs were conducted at temperatures of -24, -23, -18, -14, -10, and -5 °C. The data from these runs is graphed in figures 3.2, 3.3, 3.4, 3.5, 3.6, and 3.7, respectively. A series of increasing energy levels were tested at each of these temperatures; the minimum and maximum capacity of the equipment ranged from 0.5 Joules to 15 Joules. At least three experimental runs were conducted for each of the possible energy levels at a given temperature point, with a typical run consisting of 30 or 40 shots fired at a 1 Hz rate. The number of shots lighting of the total fired in each run was recorded, and the resulting percentage calculated. These "percent lit" points, each representing 30 or 40 shots, were then graphed against the stored energy. All of the lighting percentages for each energy/temperature point were also averaged, and a curve fitted to these average points. A good deal of scatter is found from run to run in the percentage of shots lighting for a given energy, but a definite trend exists, and the shape of the curve for each temperature point is similar. However, as temperature decreases, the energy required increases, and the maximum percentage lit decreases. This is shown in figure 3.8, which superimposes the results shown in figures 3.2 to 3.7. Figure 3.9 shows a graph of the average energy level required at each temperature point for an 80 percent or better ignition rate. This data clearly shows a linear increase in required energy as temperature decreases, with 1 Joule required at 0 °C, and approximately 1 additional Joule of energy needed for each 2.3 °C drop in temperature from that point.

Comparing the energy levels in figure 3.9 to those found in the in-engine experiments (Section 3.3), it can be seen that the energy-vs-temperature figures are similar, and that the two curves have a somewhat similar slope. This suggests that in this experiment the hindering effect of a lack of compression heating and the helping effect of operating at ambient pressure tended to cancel each other out somewhat, although low peak pressures and consequent poor compression heating were also factors in Section 3.3.

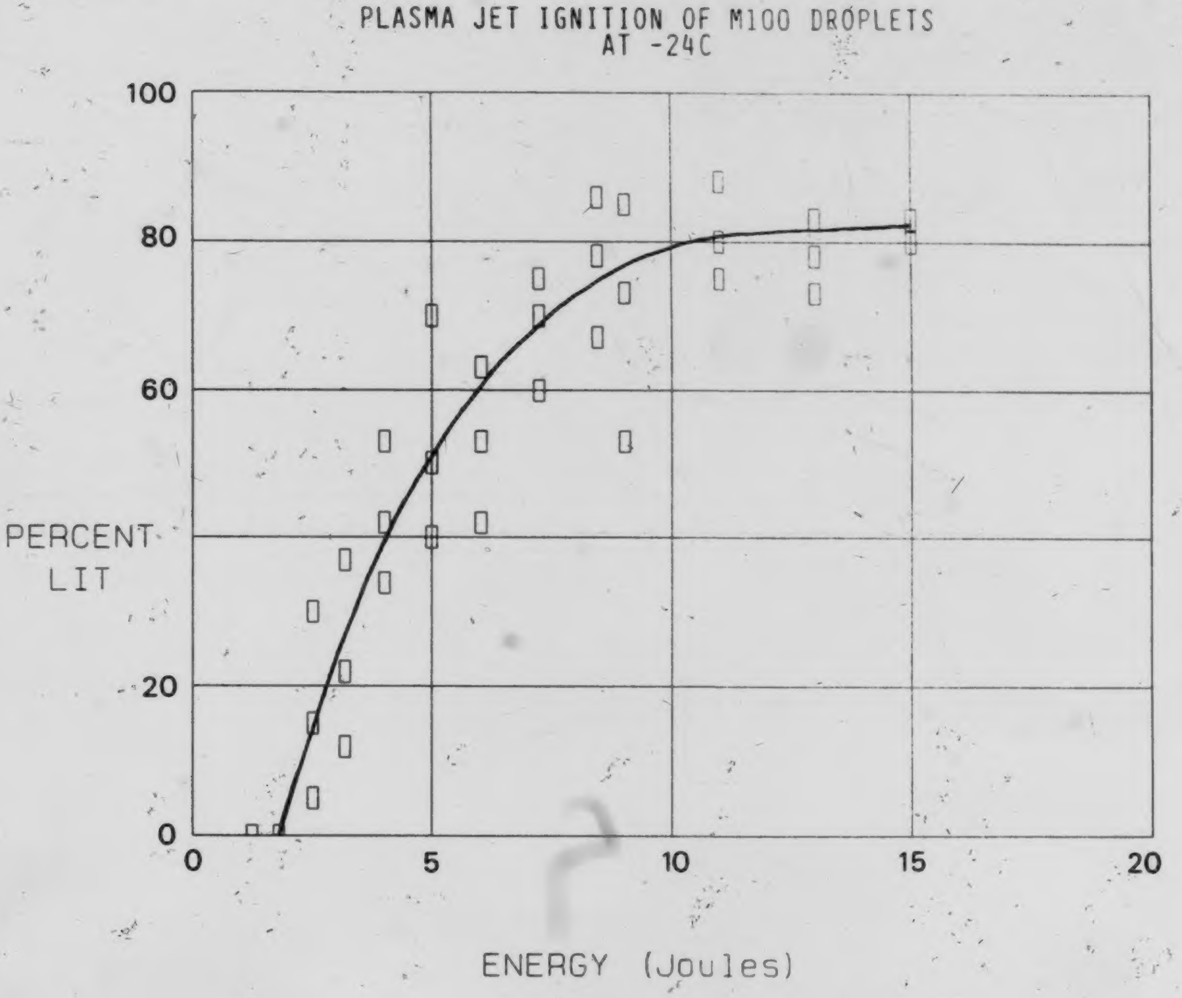

PLASMA JET IGNITION OF M100 DROPLETS
AT -24C
100
80
60
20
0
PERCENT
LIT
0
5
10
15
20
ENERGY (Joules)

FIGURE 3.2

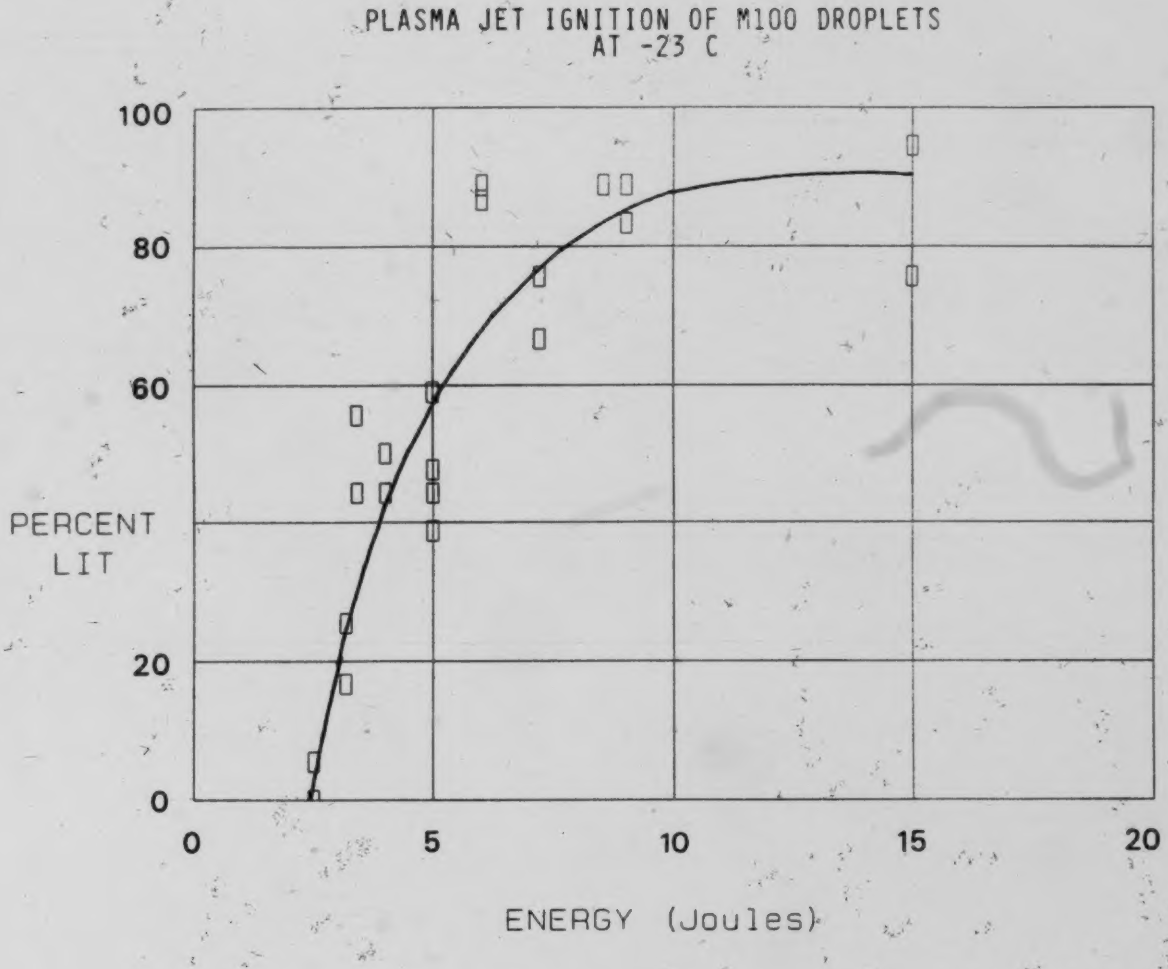

PLASMA JET IGNITION OF M100 DROPLETS
AT -23 C
100
80
60
20
0
PERCENT LIT
0
5
10
15
20
ENERGY (Joules)

FIGURE 3.3

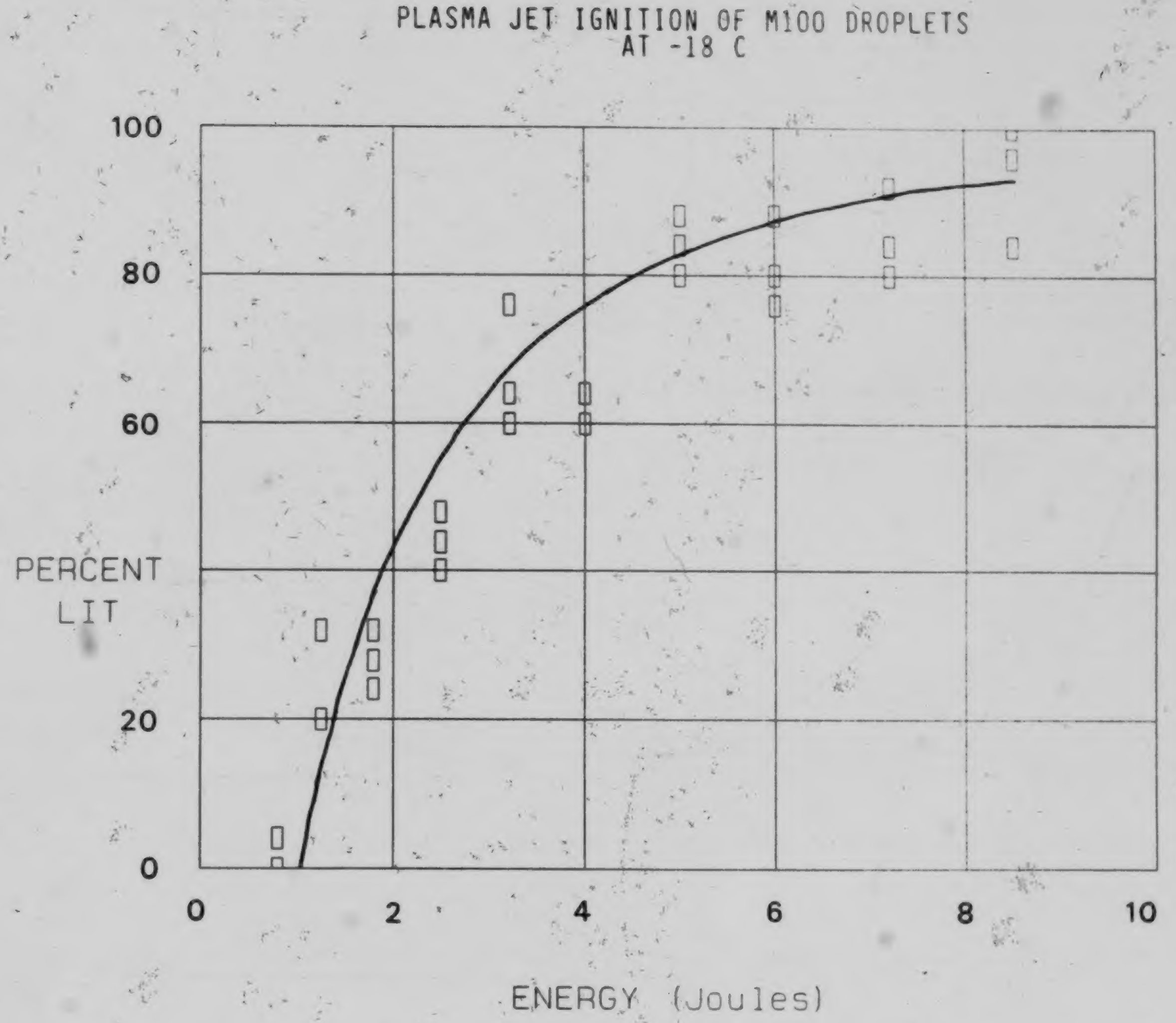

PLASMA JET IGNITION OF M100 DROPLETS
AT -18 C
100
80
60
PERCENT
LIT
20
0
0
2
4
6
8
10
ENERGY (Joules)

FIGURE 3.4

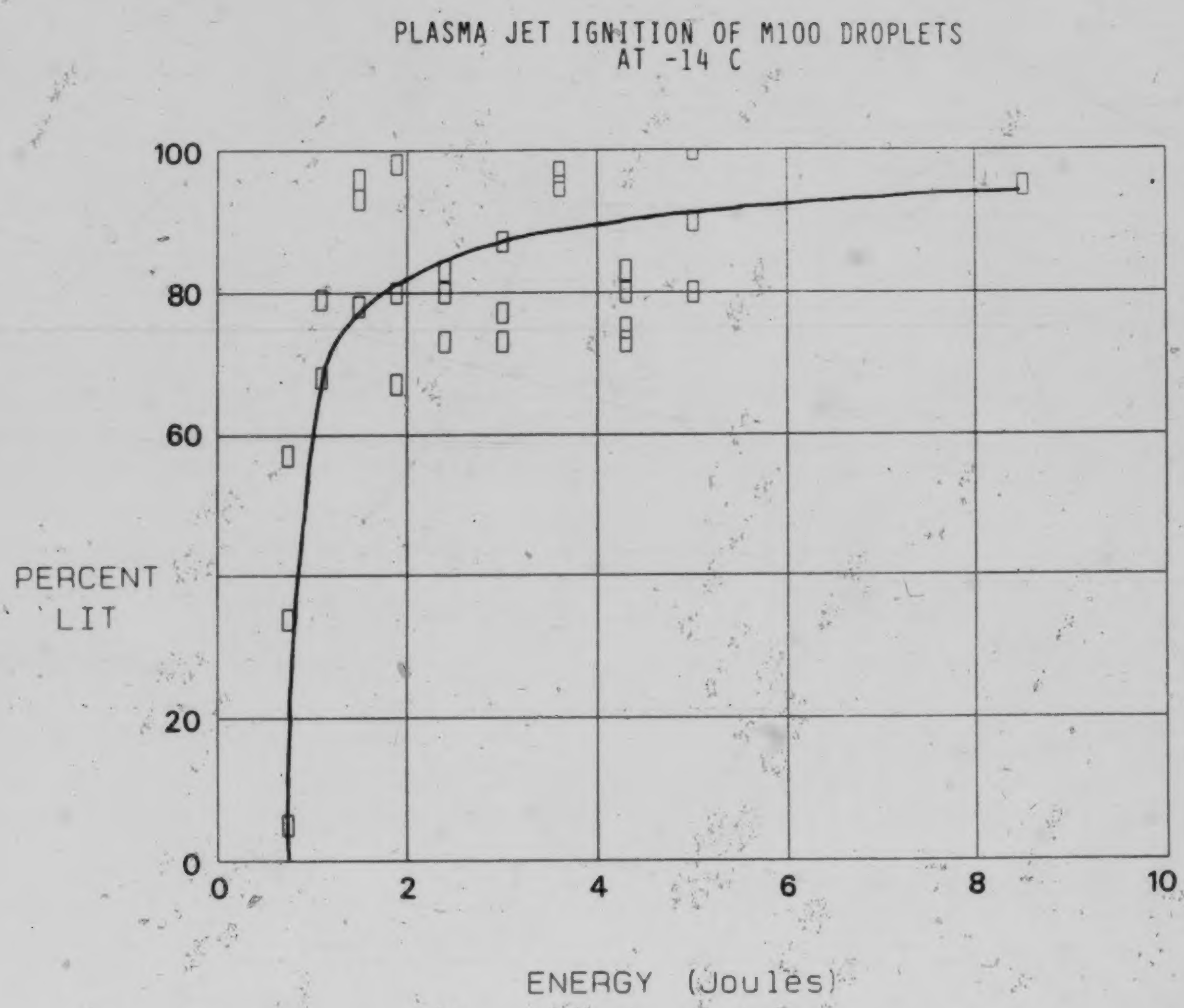

PLASMA JET IGNITION OF M100 DROPLETS
AT -14 C
PERCENT
LIT
100
80
60
20
0
0
2
4
6
8
10
ENERGY (Joules)

FIGURE 3.5

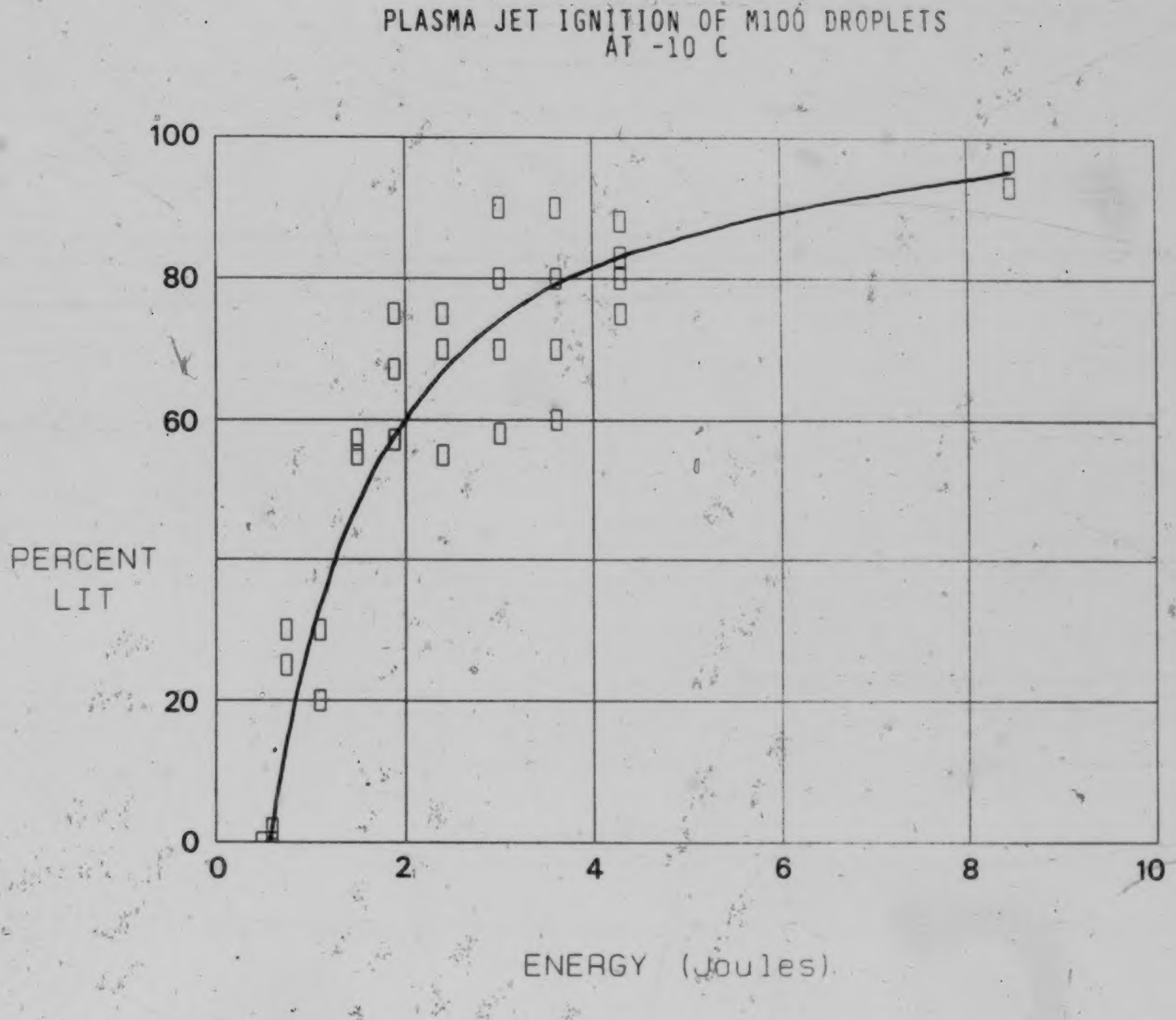

PLASMA JET IGNITION OF M100 DROPLETS
AT -10 C
100
80
60
20
0
PERCENT
LIT
0
2
4
6
8
10
ENERGY (Joules)

FIGURE 3.6

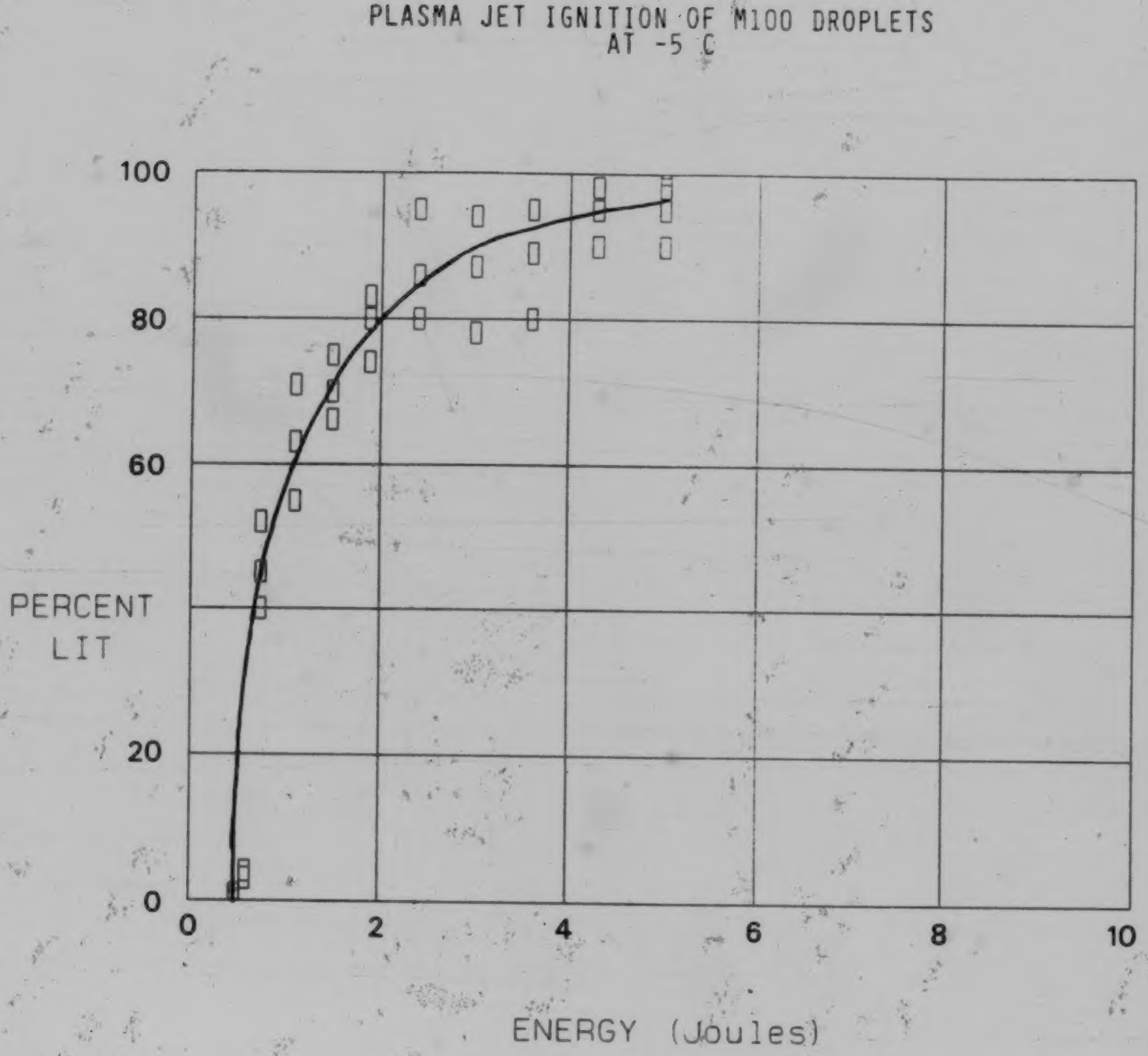

PLASMA JET IGNITION OF M100 DROPLETS
AT -5 C
PERCENT LIT
0
20
60
80
100
ENERGY (Joules)
0
2
4
6
8
10

FIGURE 3.7

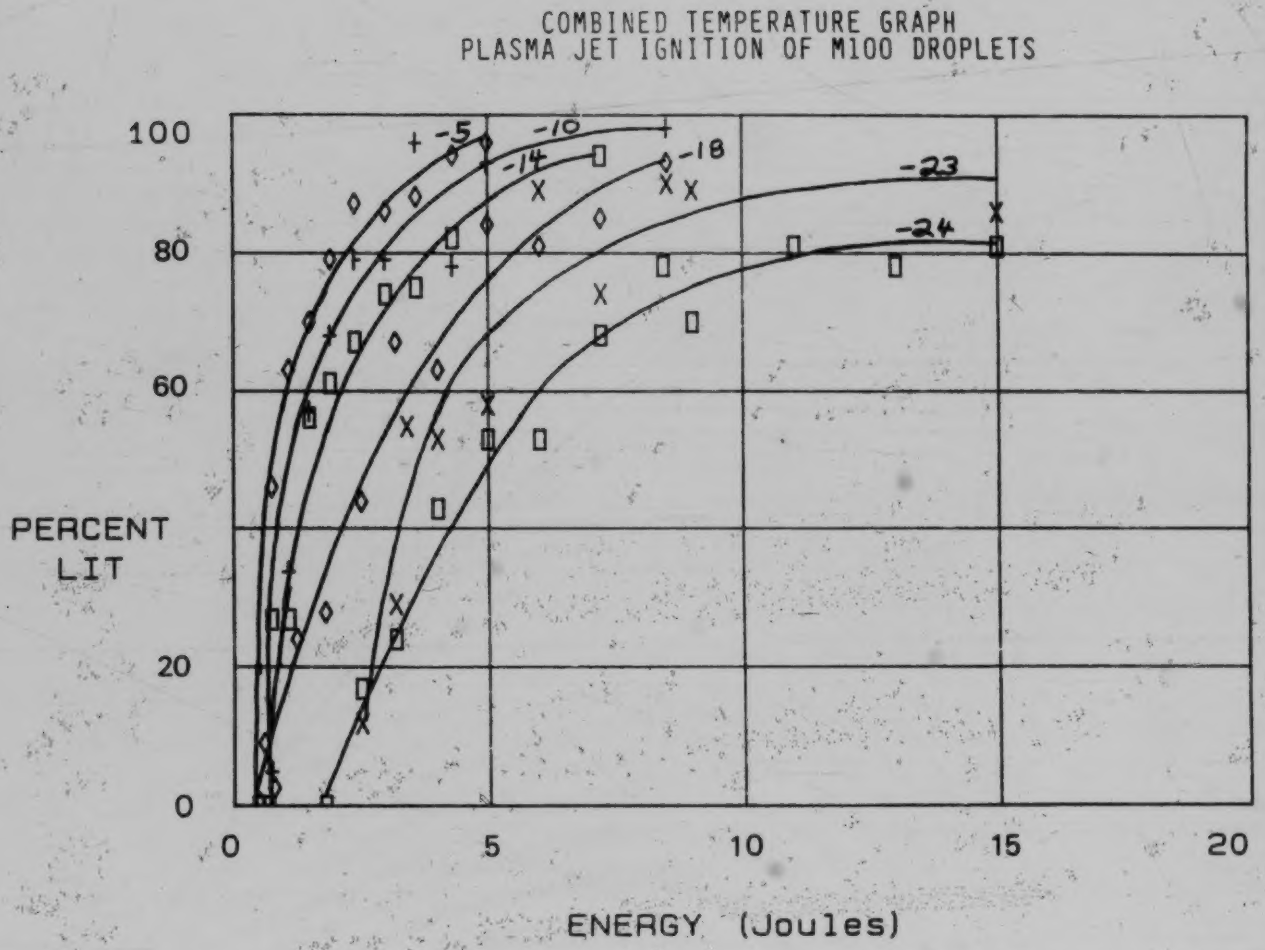

COMBINED TEMPERATURE GRAPH
PLASMA JET IGNITION OF M100 DROPLETS

FIGURE 3.8

ENERGY-TEMPERATURE PROFILE
80% PROBABILITY OF M100 DROPLET IGNITION

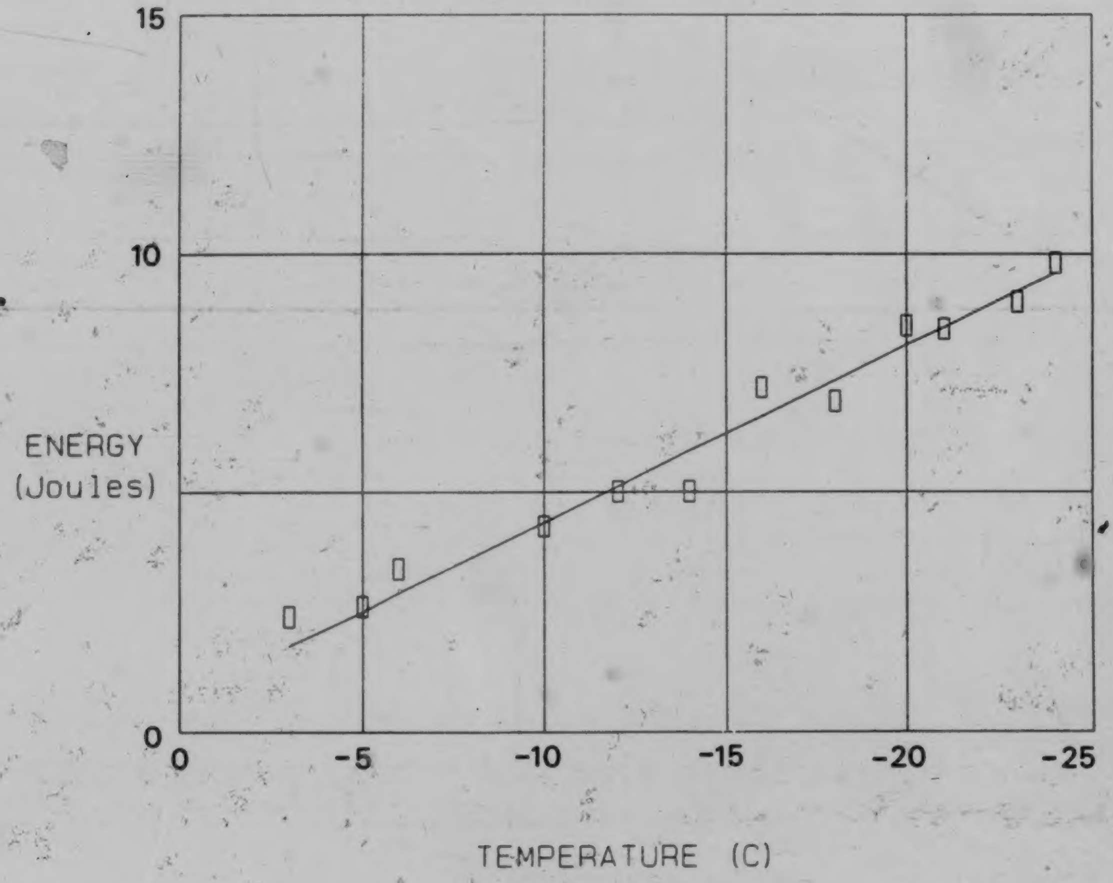


FIGURE 3.9

3.3 VOLVO IN-ENGINE TESTS

The experiments making up this study were not designed as an exhaustive analysis of the operating characteristics of the test engine, but rather as an extension of the experiment described in Section 3.2, and as a proof-of-concept for the idea of using plasma jet ignitors (PJI) as a cold starting aid in a methanol fuelled engine. The object was to establish whether or not the PJI provided a significant improvement in cold starting ability, and if so, what that improvement was. This question broke down into three parts. First, what was the lower starting temperature limit for this particular engine when fuelled on alcohol but operated with a standard ignition? Second, if an improvement in the lower limit cold starting temperature was found using the plasma jet ignition system, what was the relationship (if any) between ambient temperature and the delivered energy required for ignition? Third, was the PJI the deciding factor? That is to say: would the conventional J-gap spark plug provide similar cold starting performance if fired with the same energy as was used with the PJI at a particular temperature?

3.3.1 Cold Starting Temperature Limit Tests With Standard and High Energy Ignition Systems and J-Gap Spark Plugs.

The objects of this experiment were to 1) provide a base line result for a standard ignition system with which to compare the results from other experiments, and 2) test whether or not increased energy improved the starting performance of the J-gap spark plug on a methanol fuelled engine. Literature references, as discussed in Chapter One, cite +15 °C to +10 °C as the lowest temperature at which an unmodified spark ignitioned (SI), homogenous charge (HC) engine designed for gasoline operation can be started on methanol.

Since the in-engine tests were being conducted outdoors, with the ambient temperature not controllable, a falling temperature test was conducted on two days when the ambient temperature was much colder than that at which starting could be expected. Both tests were virtually identical in conditions and results, so only one is detailed here. In the test (#1) described below, $T_{ambient}$ was -9 °C when the test began and -11 °C when it ended. In the second test $T_{ambient}$ ranged from -9 °C to -12 °C. Measurements of the engine temperature were taken every fifteen minutes, initially of the engine coolant temperature only ($T_{coolant}$), and later of the temperature of the inner cylinder wall (T_{block}) using a contact thermometer inserted in the #1 spark plug hole after removing the #1 spark plug. The plug was immediately replaced. The latter measurements were begun when the coolant temperature had dropped to 30 °C. Starting was attempted every half hour, after temperature measurements had been taken. If the engine started, it was run for 30-40 seconds, and then shut off. The temperatures, elapsed time, and starting results for both tests are graphed in figures 3.10 and 3.11.

The experimental procedure was to start the engine on methanol fuel using the high energy plasma jet ignition and warm it into normal operating range, as indicated by the vehicle temperature gauge. The coolant thermometer indicated a temperature of 80 °C at this time. The plasma jet ignitors were then removed from the engine, and the normal J-gap spark plugs and conventional coil ignition replaced. The high energy section of the AC power supply (Section 2.3) was turned off, leaving only a conventional coil type ignition delivering 30 millijoules of energy. The rubbing contact distributor was retained because it could not be changed easily. This provided a slight advantage to the normal coil ignition system, since no energy was lost in jumping the gap found in a conventional distributor. A 10 amp charger was connected to the battery and operated between starting attempts, so that battery voltage was kept constant and as high as possible.

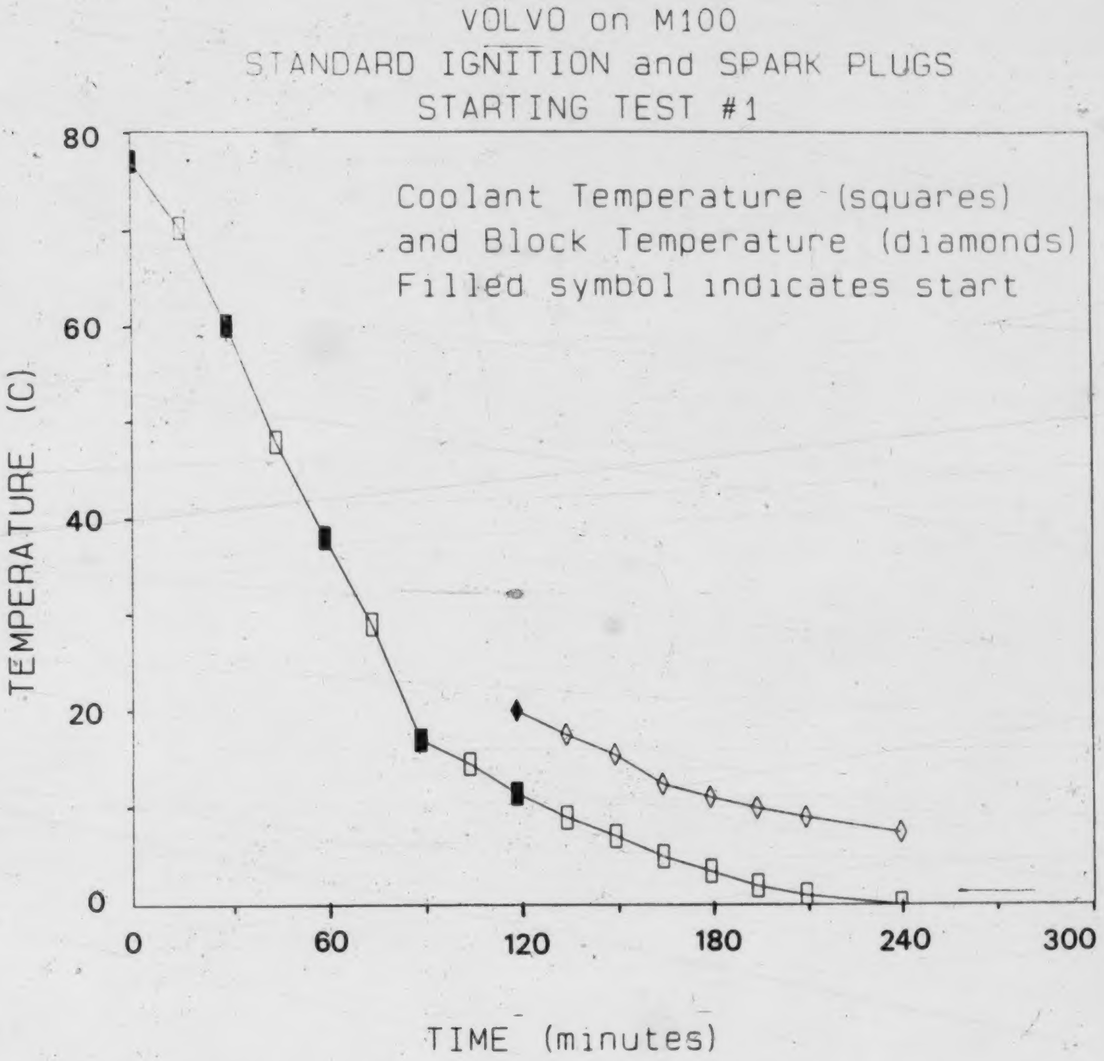

VOLVO on M100
STANDARD IGNITION and SPARK PLUGS
STARTING TEST #1
Coolant Temperature (squares)
and Block Temperature (diamonds)
Filled symbol indicates start
80
60
40
20
0
TEMPERATURE (C)
0
60
120
180
240
300
TIME (minutes)

FIGURE 3.10

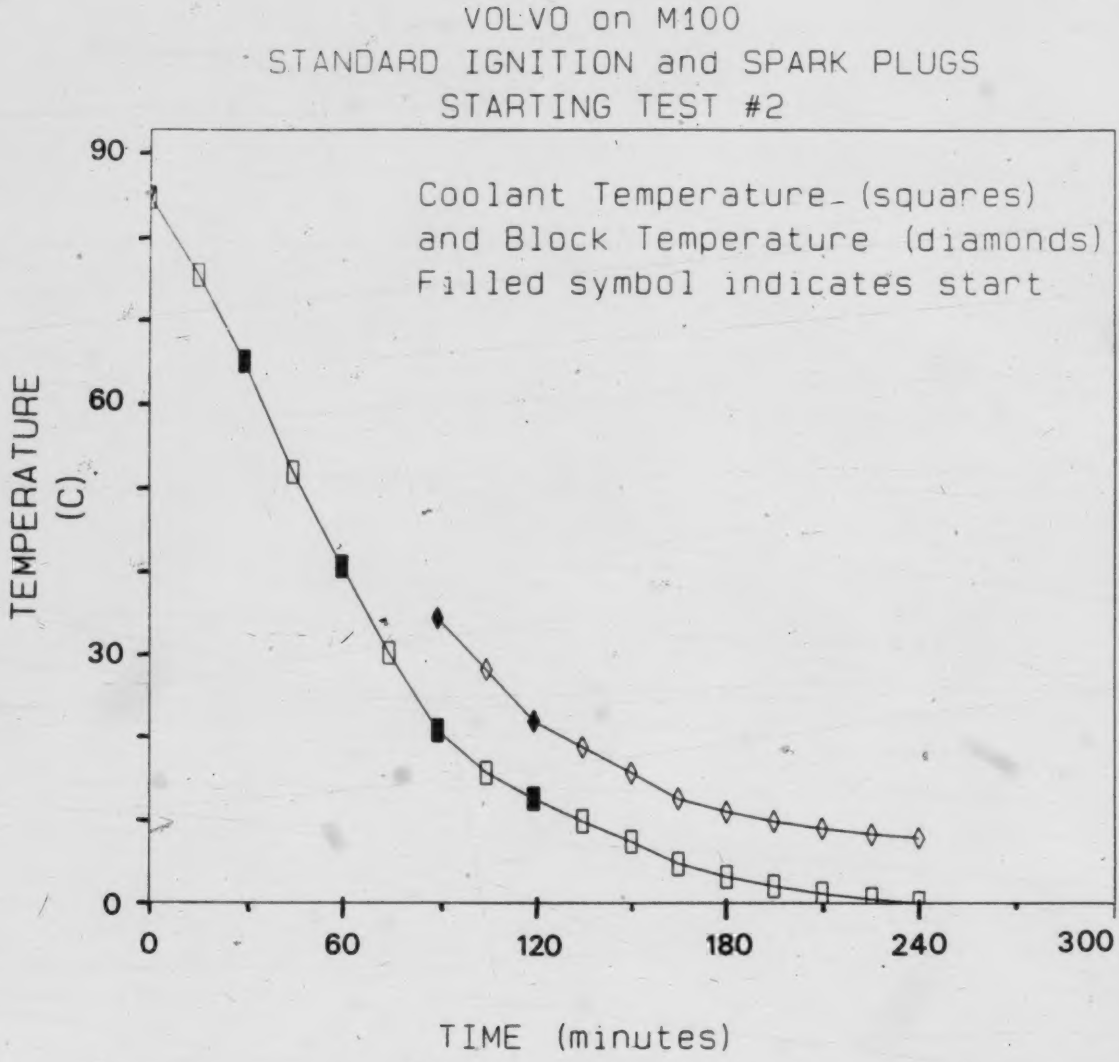

VOLVO on M100
STANDARD IGNITION and SPARK PLUGS
STARTING TEST #2
Coolant Temperature (squares)
and Block Temperature (diamonds)
Filled symbol indicates start
TEMPERATURE (C)
90
60
30
0
TIME (minutes)
0
60
120
180
240
300

FIGURE 3.11

The engine was then started, run normally for about 5 minutes, and shut off. Coolant temperature was 82 °C. Fuel temperature was -8 °C, the same as the air temperature, but of course the methanol vapourized easily as it entered the hot engine. The engine was then allowed to cool; every thirty minutes a start was tried. Starts were positive, easy and fast (within 5 seconds) until t = 90 minutes, when $T_{coolant}$ had fallen to 17 °C and T_{block} to 29.6 °C. Starting became progressively more difficult until 120 minutes had elapsed, when $T_{coolant}$ was 11.5 °C and T_{block} was 20 °C. At this point, starting took almost 45 seconds of cranking, and the engine ran very roughly and almost quit.

The next attempted start, at t = 150 minutes with $T_{coolant}$ at 7.0 °C and T_{block} at 15.5 °C, failed after 60 seconds of cranking using the standard coil ignition. The high energy section of the power supply was then turned on, and cranking tried in five second bursts, with the energy being increased each time. Starting finally occurred when the energy level being delivered to the spark plugs reached 1.9 Joules. At t = 180 minutes, with $T_{coolant}$ at 3.5 °C and T_{block} at 11.0 °C, the engine failed to start after sixty seconds of cranking in ten-second-on/ten-second-off bursts and another sixty seconds of continuous cranking, with up to 9.5 Joules being delivered to the spark plugs.

Two more attempts were made, at t = 210 minutes and at t = 240 minutes, but these also failed.

Summarizing these results, starting was possible with M100 and a normal coil ignition system at cylinder wall temperatures at or above +20 °C. At this temperature, engine operation became very rough, and starting difficult. Increasing the spark energy from 30 millijoules to 1.9 Joules allowed starting with the cylinder wall temperature at +15.5 °C. When the cylinder wall temperature had dropped to +11.0 °C, no amount of energy, up to the limits of the power supply, allowed starting on M100 using J-gap plugs.

The test ended after two more failed attempts at t = 240 minutes. At t = 270 minutes, the plasma jet ignitors were re-installed and starting attempted. Ambient temperature was -11.0 °C, $T_{coolant}$ was 0 °C, and T_{block} was +7.5 °C. A good start was achieved within five seconds using an energy of 1.2 Joules. Results of test #2, graphed in figure 3.2, were almost identical, and so will not be discussed separately.

These tests thus established three things. First, the normal ignition system would start normally on neat methanol down to block temperatures of +20 °C, with fuel and air at -9 °C. Second, a large energy increase using the J-gap spark plugs lowered the starting limit only slightly, to a T_{block} of about +15 °C. Third, the PJI provided a quick start below the lower temperature limit of the J-gap, using less energy. The improved start-ability when using the PJI is not, therefore, solely a result of higher energy deposition, but rather of properties of the PJI which differ from those of the J-gap spark plug.

3.3.2 Cold Starting Temperature Limit Tests With High Energy Plasma Jet Ignition

The object of this experiment was to test the ability of the high energy PJI ignition system to cold start the Volvo engine at various temperatures, and to establish what, if any, correlation existed between ambient temperature and minimum ignition energy for starting. The experiment was conducted outdoors over a period of several weeks, in ambient temperatures varying from 0 °C to -38 °C. As mentioned in Section 2.7, starting was attempted at intervals of approximately 12 hours, generally in the early morning and early evening. The throttle was preset to fast idle, and the extra cold-start jets open (these settings were never changed). The battery was kept fully charged by a 2 amp trickle charger, but was also at ambient temperature. Otherwise, no starting assist, such as the block heater, was employed.

The starting test procedure was to begin with the power supply set for a relatively low energy level and crank for about 10 seconds. If no firing or other indication of starting was observed, the energy was increased (by turning up the power supply in 100 volt steps) and another 10 second cranking attempt was made. This procedure was kept up for 2 minutes (i.e. 60 seconds elapsed cranking time) and if no start occurred, the test failed. Indications of firing generally occurred one or two energy settings below that which allowed starting; the engine would "almost go" when the energy neared the starting point. If the engine started it was allowed to run for 1-2 minutes, then was shut off and left to cold soak for the next trial. If the engine ran roughly but did not stall the start was recorded as a good one. If, on the other hand, the engine started and then stalled, the attempt was deemed a failure. Starting became progressively more reluctant at the ambient temperature decreased, and idling was extremely rough and "chancy" at the lower temperature limit of -16 °C. In spite of this, the engine did not actually stall within the operating period.

There were several sources of starting difficulty or failure in this test, aside from the problem being investigated. The first was the vehicle itself. From prior operation, it was known that the engine exhibited an extreme reluctance to start even on ordinary gasoline at temperatures below about -20 °C. The condition of the engine could charitably be described as "well used;" although the factory manual (Volvo 1971) specifies a compression ratio of 9.3:1 (1130-1330 kPa cylinder pressure), the actual compression was measured (warm) at

630-660 kPa. Cranking speed was low (100 rpm or less) and decreased with temperature. Esso Extra 10W-30 engine oil was used, and at low temperatures its viscosity was an extra impediment to rotation. An ordinary Delco car battery, two years old, rated new at 450 cold cranking amps was mounted in the trunk. This required 4.5 metres of #2 AWG welding cable to connect the battery to the starter, providing an additional 1 volt drop when starting. After 2 minutes, cranking speed decreased rapidly as the battery discharged.

The power supply was also a source of difficulty. In order to increase the available energy per shot above what was possible with the AC supply's internal 2 mfd capacitor, up to four additional external 8 mfd capacitors were added in parallel to give more energy storage capacity. During cranking, when several shots per second were being fired, these extra capacitors loaded down the supply so that the output voltage decreased somewhat. Measurements of actual output voltage vs indicated output voltage were made, and these measurements were subsequently used to record the actual stored energy per shot. All graphs and calculations were made using these corrected values for stored energy.

This energy shortfall at repetition rates of several Hertz became so severe when large values of capacitance were used (for temperatures below -16 °C) that another 0-1400 VDC stage was paralleled with the power side of the existing supply. This provided sufficient charging current, but eventually the booster supply overheated and was destroyed.

Because of these other sources of failure to start, the most instructive information from this test was that gathered from successful starts. This data is graphed in figure 3.12 and figure 3.13. Figure 3.12 shows the raw data points at which starts were achieved, with each square representing one start. The two points at the upper right, at -19 °C and -23 °C, are two points at which ignition could be heard to occur, but starting was not achieved. With a better engine, lighter oil, and higher cranking speeds, it seems likely that starting might have been possible. For that reason, the points are included to indicate the trend of the data. Figure 3.13 shows the same data, but with a slope intercept line plotted using the average values at each temperature. Although there is a good deal of scatter, the relationship of energy vs temperature is quite linear. Figure 3.14 shows the same average values and slope intercept line for the Volvo experiment, along with the average values and slope intercept line for those energy measurements made in the injector experiment (Sections 2.6 & 3.2) which corresponded to an 80% or better ignition rate. Although the slope of the data from the engine experiment is clearly steeper, the trend is well defined and similar for both cases.

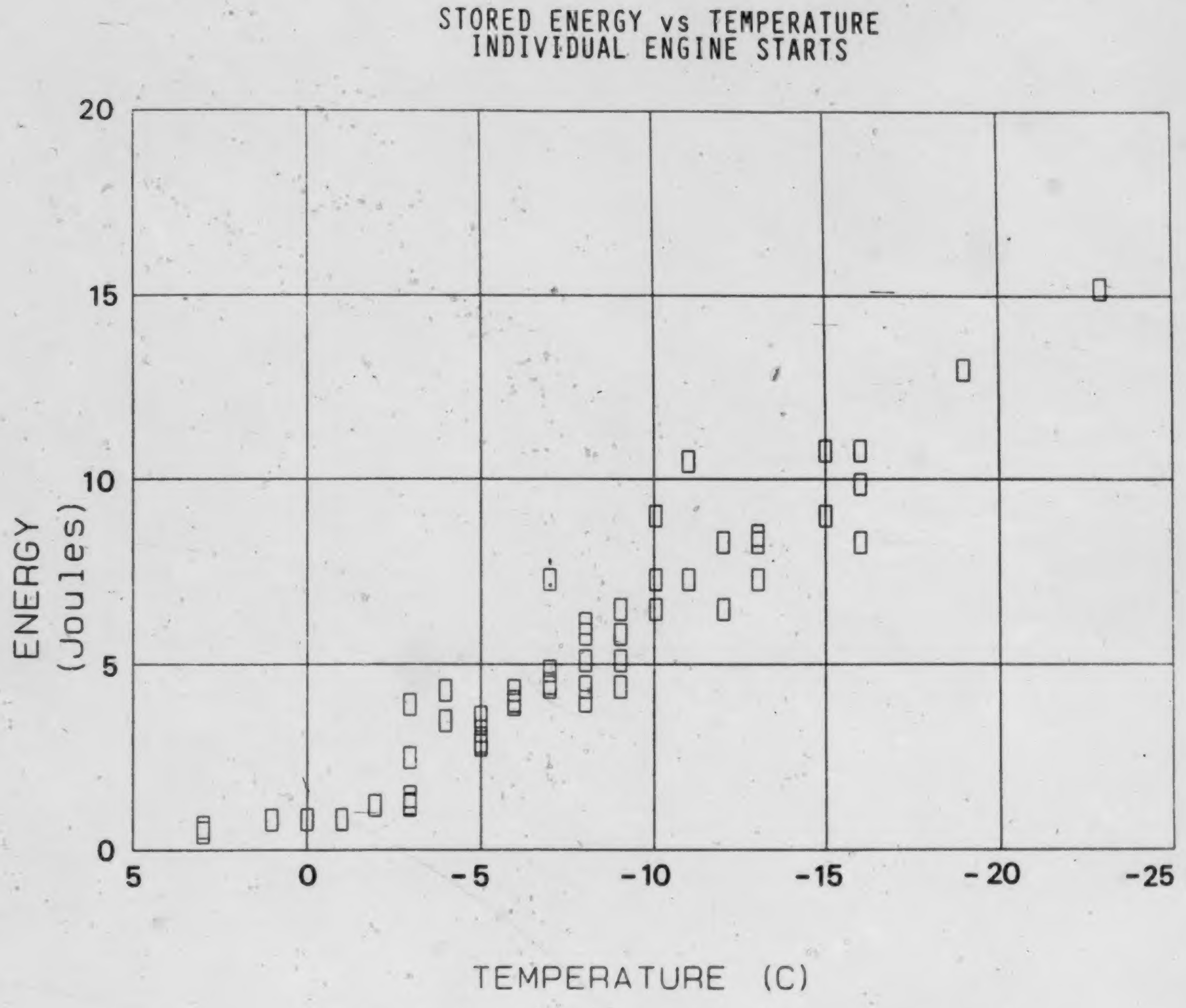

STORED ENERGY vs TEMPERATURE
INDIVIDUAL ENGINE STARTS
ENERGY (Joules)
0
5
10
15
20
5
0
-5
-10
-15
-20
-25
TEMPERATURE (C)

FIGURE 3.12

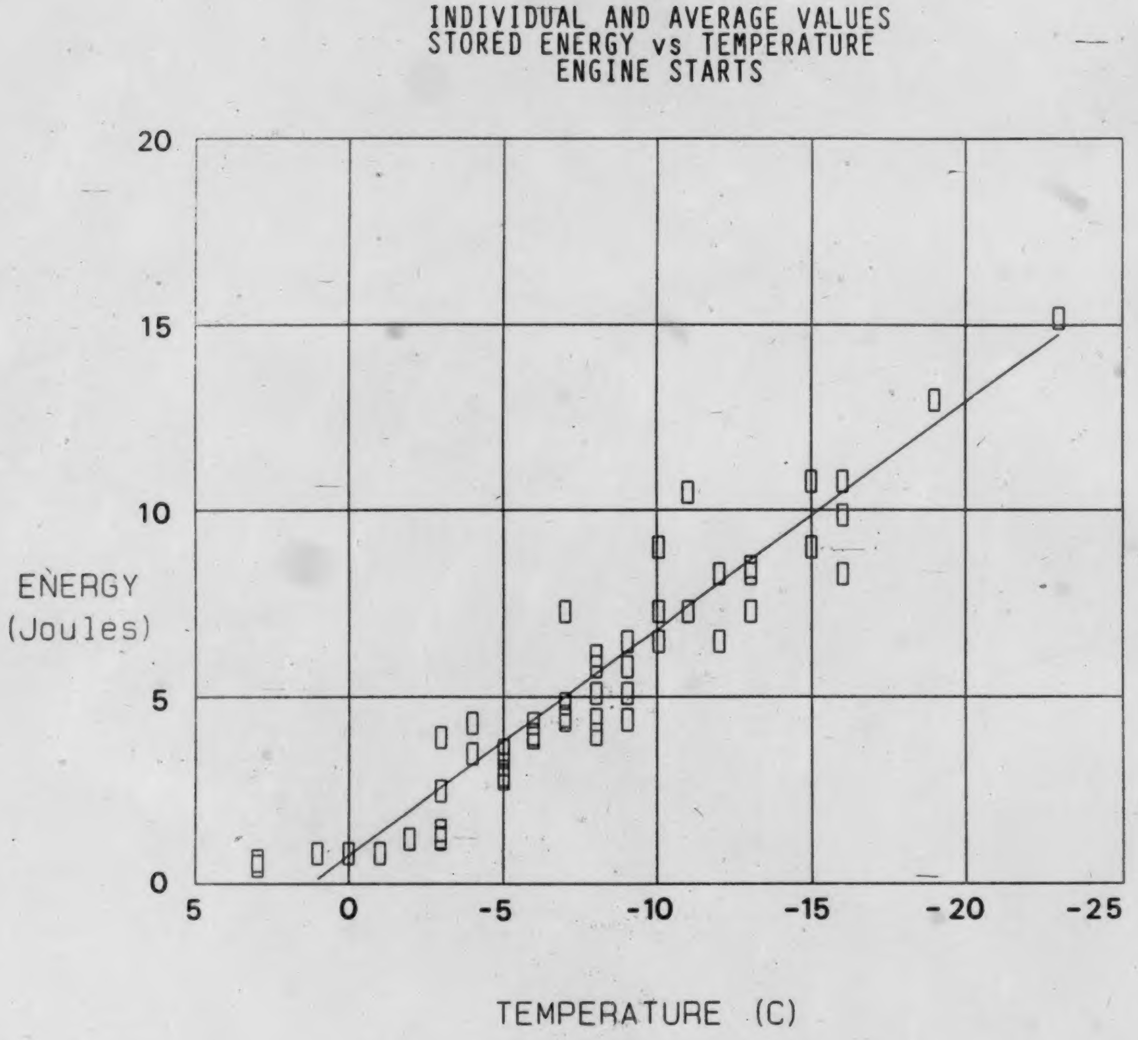

INDIVIDUAL AND AVERAGE VALUES
STORED ENERGY vs TEMPERATURE
ENGINE STARTS
ENERGY (Joules)
20
15
10
5
0
5
0
-5
-10
-15
-20
-25
TEMPERATURE (C)

FIGURE 3.13

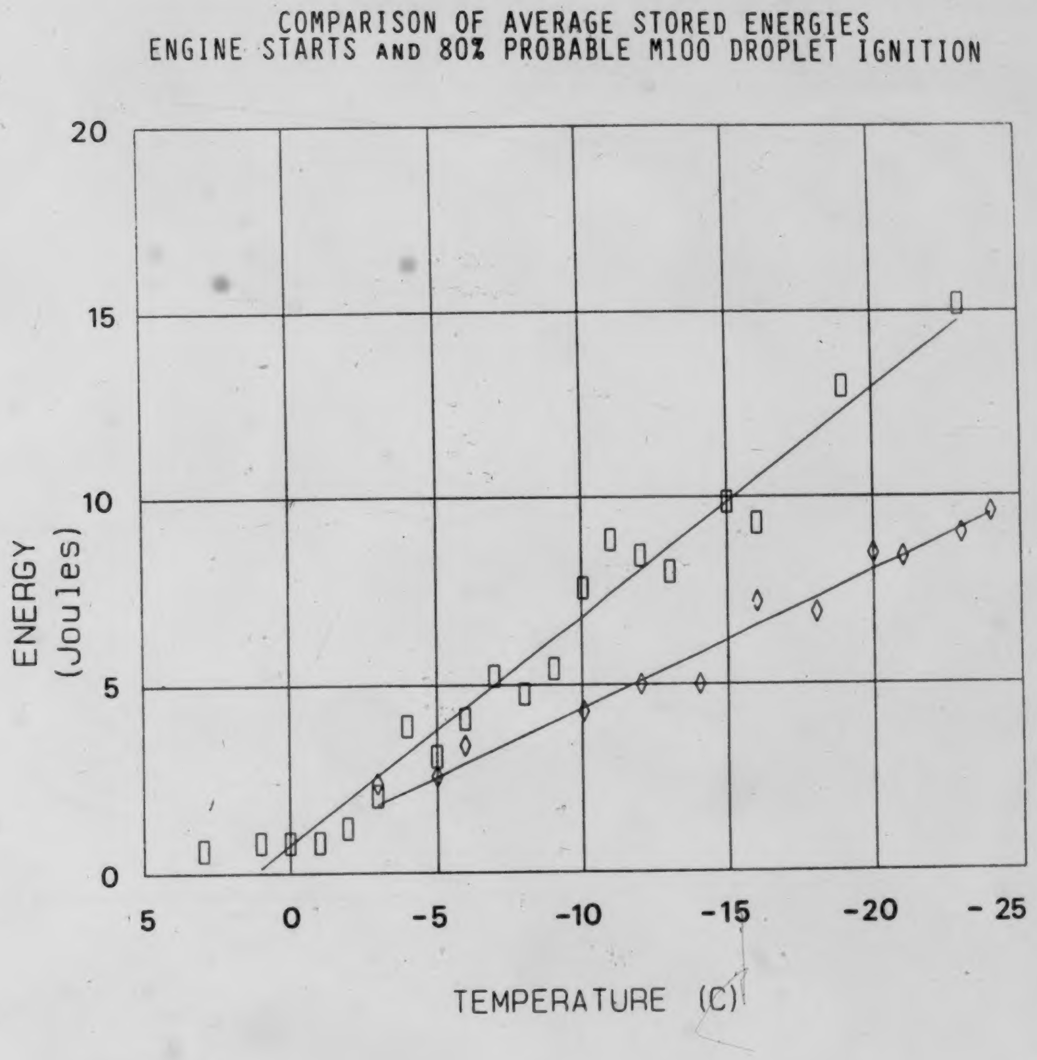

COMPARISON OF AVERAGE STORED ENERGIES
ENGINE STARTS AND 80% PROBABLE M100 DROPLET IGNITION
20
15
10
5
0
ENERGY (Joules)
5
0
-5
-10
-15
-20
- 25
TEMPERATURE (C)

FIGURE 3.14

CHAPTER 4: DISCUSSION

4.1 GENERAL RESULTS

The experiments described in the previous chapters had three main objectives. First, would a pulsed plasma jet ignitor ignite neat (100%) methanol at low or sub-zero temperatures? Second, if such ignition was possible, what was the relationship between energy and temperature? Third, if the device worked in a laboratory bench test, would it improve the cold-starting characteristics of a real automobile engine running on neat methanol? The answers to all three questions is clearly "yes."

The initial experiment, using a plasma jet ignitor and a pool of chilled methanol, showed that the plasma jet ignitor would regularly light the cold fuel in cold air at temperatures from +15 °C down to 0 °C. Ignition at temperatures below this was achieved, but because of the crude experimental setup, results were too scattered to be useful other than as an incentive to further investigation. The data indicated that ignition at a given temperature became steadily more probable as energy was increased, rather than being a step function. The results also clearly indicated a relationship in which the stored energy required for ignition increased as temperature decreased. This relationship appears exponential in nature, and the curve trends sharply upwards as the temperature approaches the freezing point. It is worth noting that the average energy required for a 100% ignition rate at 0 °C in this experiment was 2.5 Joules, which is higher than the average figure of 0.81 Joules at -5 °C found in the second experiment. This difference is almost certainly a consequence of the use of a pool of methanol in the first case, and a cloud of droplets in the second case. In the first instance ignition would depend either on heating of a portion of the methanol pool by the plasma plume (before that heat could be drawn away by the bulk of the pool), or on droplets being kicked up, heated, and ignited by the plasma plume and its blast wave. Either of these modes of operation would be much more difficult and uncertain, and so would require more energy to accomplish.

The second experiment, in which both lower temperatures and continuous runs of repeatable shots were possible, pushed the temperature limit of the PJI's capability down to -24 °C. This does not appear to be an ultimate limit, but rather was the lowest temperature which was maintained for long enough to gather a large body of data. During initial testing, of the setup, ignition was easily achieved at -30 °C in still air (i.e., without the airflow fans turned on) with energy levels of 3.4 Joules, but it was not possible to gather enough data to make a valid sample. Experiments for the still air case were not continued; it was felt they had little relevance to the conditions found in cold starting an automobile engine. Likewise during initial testing, a single test run of 50 shots at -28 °C showed a 92% lighting rate at an energy of 9.4 J with the airflow fans turned on. This temperature was not reached again during this experiment, and so the results could not be confirmed by multiple trials. Accordingly, this data point was not included in the results graphed in Chapter 3. There was certainly no indication that a lower temperature limit had been found, although it was observed that the percentage of shots lighting reached at plateau of approximately 80% at 9+ Joules and -24 °C. One possible contributing factor is discussed in Section 4.4 on ignitor limitations.

As noted earlier, the average energy level for an 80% or better rate of ignition at the -5 °C temperature point was 0.81 Joules, and rose to 9 Joules at -24 °C in a relatively linear fashion. The individual graphs of energy vs percent lit resembled, as was the case in the first experiment, exponential curves. These energy level rose sharply as higher percentages of ignition were reached; nonetheless the overall energy vs temperature relationship was quite linear. Part of the reason for the sharp rise in individual curves could be ignitor limitations, but this would not account for the -5, -10, -14, and -18 °C cases, where ignition rates near 100% were reached at energies well short of the ignitor's ultimate energy capacity.

A more likely reason for the sharp upturn in the curves is that the larger plasma plume produced by higher energies would intersect and ignite more fuel droplets, thus making flame propagation more certain. This is difficult to quantify, since conditions were quite turbulent, making fuel droplet location somewhat uncertain. Attempts to photograph this process were not successful, so this phenomenon can only be inferred from direct naked eye observations.

The third and final set of experiments, on the 1973 Volvo, were also successful, although the experiment was plagued with breakdowns. To establish a baseline against which to measure the performance of the PJI system, two tests, using standard spark plugs with regular and high energy ignition systems on an unmodified engine with M100 fuel, were conducted. These tests gave two definite results. First, the engine would not start on the regular ignition when block temperatures dropped below +18 °C (coolant temperature 11 °C), and second that the addition of a high energy plasma jet ignition system to the regular spark plugs only improved the starting temperature range by about 3 °C. This established a lower limit for this engine against which the performance of the PJI system could be compared.

Cold starting tests with the PJI system and an AC operated power supply showed that the PJI provided a great improvement in cold starting an automobile engine under realistic conditions, and that there is a well defined relationship between ambient temperature and energy required for ignition. The lowest temperature at which starting was achieved was -16 °C, with an energy level of 10-11 Joules per stroke per ignitor. From a survey of the published literature and from conversations with other researchers in the field, the -16 °C starting temperature limit of the PJI system is the lowest temperature recorded anywhere for an otherwise unmodified homogenous charge engine. The lowest previously reported cold start for an HC engine on M100 fuel was -6.5 °C; this result improves on that by almost 10 degrees.

It is unclear whether or not -16 °C is an absolute lower limit, or a limit of the equipment being used. Certainly the ability of the power supply to deliver sufficient energy was a limiting factor; even with two secondary stages in parallel, voltage drop and consequent power loss was a problem. Power supply temperature was also a factor. The capacitors used diminished in capacity as they were cooled, and so had to be kept indoors in between starting attempts. Data points at -19 °C and -23 °C were found where firing appeared to occur but starting did not. This may indicate that the failure to start at these temperatures was a problem either of slightly insufficient ignitor energy, or a mechanical limitation of the vehicle itself. The mechanical handicaps of the car have already been described in detail elsewhere. In brief, they included low compression, slow (80 rpm) cranking speed, insufficient battery capacity, long battery cables causing voltage drop at the starter, a cold battery, a heavy grade of engine oil, and general decrepitude.

Also to be considered when looking at the results is the starting procedure employed. Short periods (10 seconds) of cranking followed by an equal period of resting were used, with an increase in energy after each try if starting did not occur. Some warming of the engine would certainly occur after 60 seconds of cranking had elapsed, if only from compression heating and friction. Compression, in particular, would likely be improved, since liquid methanol fuel would help to seal the piston rings when enough had accumulated. Long periods of continuous cranking have been used by other researchers, so their use in this case does not appear to seriously invalidate the results obtained. On a more commercial note, it is important to understand that the cranking time employed would probably be unsuitable for a production vehicle. A normal gasoline-engined automobile generally starts in five to 10 seconds, so that is what consumers have come to expect. From published results mentioned in Chapter 1, it is clear that an increase in cranking speed would have been a useful modification in shortening the overall cranking time, but the equipment to do this was not available. The fact is that good results were obtained in spite of the equipment used, rather than because of it.

It therefore seems reasonable to infer that similar or better cold starting performance could be achieved on an engine optimized for M100 fuel which was mechanically superior to the Volvo engine. Furthermore, if a PJI system was combined with one or more of the other promising starting assist systems mentioned in Chapter 1, such as prompt exhaust gas recirculation or catalytic DME generation, it is likely that the energy requirement could be significantly reduced. This would be a great benefit in any practical implementation of a PJI methanol cold starting system, because two of the major drawbacks in using such a system are ignitor erosion and the size and complexity of the power supply. A very large (electrically and physically) power supply was needed for this experiment, and ignitor erosion, although not explicitly measured, was visibly severe. High power levels are needed only for cold starting; once the engine is running and warm, the energy used in a normal automobile ignition system is quite sufficient for normal operation. Therefore, the equipment needed for cold starting would be idle most of the time, and so would represent dead weight and extra cost. Any reduction in the energy required by the starting system would thus allow a smaller, lighter power supply to be used, while the reduced energy level would lessen erosion problems. As this experiment has shown, cold starting on M100 fuel and a PJI system alone is possible; in practice such a system by itself might not be an optimum and cost-effective method.

A great deal of investigation will be required to answer the questions posed by any attempt to incorporate a PJI starting system into a commercial automobile, and it may be that some better cold starting method will be discovered and used. Nonetheless, the sub-zero results obtained and described here provide a useful starting point for future research. Moreover, the -16 °C cold starting temperature achieved is a substantial improvement over those obtained previously for homogenous charge engines burning M100 fuel.

4.2 FUEL HEATING AND VAPOURIZATION

The experiments described in Sections 3.1 and 3.2 leaves no doubt that a plasma jet ignitor is capable of igniting methanol fuel at sub-zero temperatures under the conditions used in the experiments. They also show a clearly defined relationship between the energy required to achieve ignition and the ambient fuel and air temperature. Furthermore, the second experiment showed that there is also a correlation between the energy supplied to the ignitor and the percentage of the shots that ignited. This suggests a relationship between plasma puff size and droplet density near and distance from the ignitor. Since the likelihood of one or more droplets being identically positioned from shot to shot is not only small, but unpredictable, it then follows that the larger and more energetic the plume, the greater the chance of its intersecting, vapourizing, and igniting one or more droplets. However, the converse is also true; the larger volume of the puff grows, the lower its average energy density becomes. The low air temperatures, high airflow rates (4-10 m/s) and slow firing rate (1 Hz) in the chamber used in this experiment make it unlikely that methanol vapour from a droplet vapourized (but not ignited) on one shot would be present for a subsequent shot. Therefore, any fuel that ignited probably did so as a result of a process independent of preceding shots, rather than as the result of some cumulative effect.

Even a relatively low energy PJI discharge of 1 Joule (stored energy) contains enough energy to vapourize a large droplet several times over, as the following calculation shows. The energy required to raise methanol from an ambient temperature of (for example) -10 °C to vapourization temperature (+65 °C) is 2.54 J/gram/°C; the additional latent heat of vapourization is 1101.1 J/gram.

Therefore, a droplet of radius 0.20 mm, having a volume of 3.35×10^{-5} cm^3 and a mass of 2.64×10^{-5} grams, would require:

$$2.54 \times 75 \times 2.64\text{x}10^{-5} + 1101.1 \times 2.64\text{x}10^{-5} = E$$

$$E = 0.0340 \text{ Joules}$$

to be heated and vapourized. This is only about a third of the energy available in the discharge from the plasma plug, assuming a 10% conversion efficiency. This calculation is somewhat simplistic, of course. It assumes an interaction with only one droplet, rather than several. Droplet sizes will vary, and some would likely be of smaller radius than 0.20 mm. Perfectly efficient transfer of energy from the plasma puff to the droplet cannot be assumed, either. However, within these assumptions, it is clear that an excess of energy is available.

The efficiency of heat transfer from a plasma plume to a droplet is not known, and no attempt was made to measure it in these experiments. Nonetheless, a simplified calculation using the data for the injector experiment at -10 °C provides an interesting estimate. The minimum average stored ignition energy for an 80% or better shot-to-shot ignition rate was 4.3 Joules/shot. If we assume, as before, interaction with a single droplet of 0.20 mm radius, and also assume that the conversion efficiency of stored electrical energy to heat energy in the PJI is 10% (Chapter 2), then the energy available in the plasma plume is 0.43 Joules. With 0.034 Joules needed to heat and vapourize one droplet, this corresponds to an energy transfer efficiency from plume to droplet of 8%. If there was more than one droplet involved (as could easily be the case), the energy transfer efficiency would, of course, be higher. Of course, if one droplet ignites, the heat from its burning is available in addition to that of the plume, and so increases the chance of igniting other droplets. The detailed mechanism by which the plasma plume interacts with fuel droplets was not the subject of these experiments, and so is beyond the scope of this discussion. Nonetheless, it seems that whatever mechanism operates, whether it be conduction or radiation, does so in a reasonably efficient manner.

4.3 COMPRESSION HEATING

Compression heating was not present in the experiments described in Sections 3.1 and 3.2, but was present in those described in Section 3.3. A simplified worst-case analysis of the contribution of compression heating was done for this experiment; this shows that compression heating is a negligible factor in the cold starting process in this engine.

A number of simplifying assumptions are made. First, the maximum compression temperature is taken as 100 °C, which, according to published results, is a reasonable (if not optimistic) figure for a cold engine with compression of 666 kPa. Second, cranking speed was taken to be 100 rpm, which is about 20 rpm higher than was measured. Third, it was assumed that the maximum temperature rise, and thus maximum heating, would take place within 10° of TDC (top dead center), making the heating period 1.668×10^{-2} seconds. Fourth, the fuel charge was assumed to be 0.045 cm^3 of methanol (approximately one injector shot), and this charge was assumed to have broken up into 1000 relatively coarse uniform spherical droplets. Droplets from a direct injection system would be much finer, but in a homogenous charge engine droplets of this size are not likely to exist in large numbers. Therefore, the volume V of each droplet was 4.5×10^{-5} cm^3, radius r was 0.22 mm, and mass M was 3.5×10^{-5} grams. The density ρ of neat methanol is 0.787 g/cm^3. The methanol was assumed to be at +10 °C; any fuel temperature below this would, of course, require still more heat to reach vapourization temperature. The actual energy required to raise the droplet temperature from +10 °C to +65 °C is 4.89×10^{-3} J; the additional energy required to vapourize the droplet is 0.0385 J. Thermal diffusion effects within the droplet were neglected; thermal conductivity was taken to be almost instantaneous in a body this size. Lastly, since the cold droplet was to be surrounded by much warmer air, thermal radiation from the droplet was neglected.

The heat flux Q/A available during compression is:

$Q/A = h\Delta T$

where: $h = 8.5 \times 10^{-3}$ J/cm²•s•K
(Jorgensen 1988)

$\Delta T = (100-10) = 90$ K

$\therefore$ $Q/A = 0.765$ J/cm² s

The heat flux required to raise the droplet from ambient temperature (+10 °C) to vapourization temperature (+65 °C), neglecting the additional latent heat of vapourization of 1101.1 kJ/kg needed to actually vapourize the droplet, is given by:

$$Q/A = (C_p\ \rho\ V\ \Delta T)/(A\ \Delta t)$$

where: $C_p = 2.54$ J/g

$\rho = 0.787$ g/cm³

$V = 4.5 \times 10^{-5}$ cm³

$\Delta T = (65-10) = 55$ K

$\Delta t = 1.668 \times 10^{-2}$ seconds

$A = 6.08 \times 10^{-3}$ cm²

$\therefore$ $Q/A = 48.78$ J/cm² s

Thus, the heat flux Q/A required to heat a droplet from +10 °C to +65 °C during cranking is over 63 times what is available from compression heating. This does not include the latent heat of vapourization (1101.1 kJ/kg), which is over and above this figure. Clearly, under even the most optimistic assumptions, compression heating of fuel droplets does not contribute significantly to their vapourization and ignition in the cold starting process.

The only possible exception to this would be in the case of very small fuel droplets; however, droplet size would have to be substantially smaller than 0.20 microns diameter to be heated and vapourized when cranking a cold engine. Droplets this small are not formed even by high pressure fuel injectors; their occurrence is therefore quite unlikely in the fuel system of a normal HC engine.

4.4 IGNITOR LIMITATIONS

Examining the graphs at different temperature points of energy versus the percentage of shots lit (figures 3.2 to 3.7), it is clear that energy required for ignition increases as temperature decreases. However, these graphs also show that the maximum percentage of shots lighting decreases as the temperature goes down, regardless of how much extra energy is supplied. The exact reasons for this are not clear from the experiments performed, but the linear nature of the data graphed in figures 3.9 and 3.13 suggest that the problem is something of an anomaly. One possible reason for this apparent limit is the cavity size of the plasma jet ignitors used. In order to eliminate one variable in results from different experiments, the same size cavity was used in all experiments and at all temperatures. As constructed, the ignitors were optimized for stored energy levels between 1 and 10 Joules, and the cavity volume was selected accordingly. When the ignitor is fired, the cavity contents are heated to a plasma, which is then expelled. If more energy is supplied than the ignitor is designed to accept, the cavity will literally run out of fuel before all of the additional energy can be used. Making the cavity within the ignitor larger does, of course, make more mass available to be heated to plasma; this additional plasma would probably improve the ignitor performance at very high energies and very low temperatures. However, that same increase in cavity dimensions also makes the plug perform poorly at lower energy levels, so that more energy would be required to create a plume at more moderate temperatures than was needed in this experiment. Thus, any real-world application of this device would, for maximum effectiveness, have to be designed with operating temperature and energy ranges in mind.

4.5 METHANOL ENTRAINMENT IN THE PLASMA PLUME

Unlike a regular J-gap ignitor, in which plug wetting causes shorting of the gap, the performance of the PJI in lighting cold methanol was improved when a film of methanol existed on the orifice plate of the plug. This freedom from shorting occurs, of course, because the electrical discharge does not take place across the orifice plate. Plume length and luminosity increased, and the sound of firing was much louder. All of these factors indicate that some small amount of methanol fuel is being picked up by the plume as it exits the orifice plate. Another mode by which methanol might be entrained in the plasma plume, and thus improve the ignitor's lighting ability, would be if one or more fuel droplets were drawn into the plasma puff through the turbulent eddies that occur at the sides of the plume behind the flame front. The effects of a fuelled plug have been described in the literature; one of the main indications is an increase in plume size and luminosity, and one of the main results is the creation of free radicals and partially burned fuel within the plasma plume. Both of these factors are known to improve the ability of the PJI to ignite a variety of types of gas mixtures, so it seems possible that a similar effect might be operating in the case of cold methanol ignition as well.

4.6 THE ENHANCED PJI

The enhanced plasma jet ignitor, described in Section 2.2, was originally conceived as a means of eliminating one variable in a specific experiment. That experiment was not concerned with the performance of the enhanced PJI per se, since initial tests showed that its energy consumption was identical to the normal PJI. However, the self-fueling characteristic of the enhanced PJI (EPJI) would seem to be of additional interest in the area of cold starting. When the sintered bronze end of the EPJI is wetted by even a single droplet of methanol, the enhancement in plume length and luminosity lasts for at least 20 shots, even if no further fuel is added. This is not the case if a standard PJI is filmed with a similar amount of methanol; the fuelled plume effect disappears within a few shots. Further, even if the bronze material of the EPJI is saturated, the ignitor is not choked off or shorted out. Since it seems unlikely that a standard PJI in an engine cylinder would be evenly filmed by splashing unvapourized fuel or airborne fuel droplets on every stroke, it also seems unlikely that the ignitor plume would be consistently improved. An EPJI, on the other hand, would need to pick up only a single droplet to give an enhanced plume for a further 20 shots or so. Intuitively, it seems more likely that a methanol droplet would wet the ignitor at least 1 in 20 times, rather than 1 in 5, for example. The EPJI would probably, therefore, provide a consistent improvement in fueling the plasma plume as it left the orifice.

As has been mentioned, an in-engine test of this idea was tried, and the test failed because the sintered bronze discs, epoxied to the steel orifice plates, became detached. This may have been because of a failure of the adhesive, or it may have resulted from a collision of the lengthened ignitor with the piston tops. Since no damage was evident on the recovered discs, the former reason seems more likely. Further testing of this idea would almost certainly prove worthwhile, if a better method of attachment could be devised.

4.7 SUMMARY

As was stated at the beginning of the chapter, the experiments described here, although somewhat crude, had positive results, and the data obtained gives a good indication of the ability of the plasma jet ignitor to ignite cold methanol. As is often the case, further questions were raised by the successful results obtained, and more avenues of exploration suggested. What the ultimate utility of these results will be cannot be predicted, but early indications are that at least some of the data will be of interest to other researchers studying M100 cold starting. Certainly, the energy-temperature characteristics of the plasma jet ignitor for cold starting work measured in these experiments show that the PJI has a clear advantage over the conventional J-gap ignitor in this application.

CHAPTER 5: CONCLUSION

The results of this study show that the pulsed plasma jet ignitor can successfully be used to ignite 100% or neat methanol fuel (M100) at temperatures down to -24 °C, and that a well defined linear relationship between energy required for ignition and ambient temperature exists. An in-engine test of these ignitors and a high energy power supply gave successful cold starts at temperatures down to -16 °C in a 1973 Volvo running on M100 fuel. Starts below this temperature were attempted but were not successful; equipment limitations are believed to be responsible. There is no direct evidence to suggest that this temperature is an ultimate limit of operation for the PJI in this application.

Three sets of experiments were done. The initial test used the PJI to ignite a pool of chilled 100% methanol. A thermostatically controlled chilled block and air chamber were constructed, and the ignitor under test mounted above. Tests of a normal spark plug showed that it would not ignite the methanol pool if the temperature was below the flash point of 11 °C. With the PJI, reliable ignition was obtained from temperatures of +15 °C to 0 °C, but below this temperature the blast effect of the plasma plume dispersed the pool before it could be ignited. The energy needed for reliable ignition ranged from 0.25 Joules to 2.5

Joules as the temperature decreased. This experiment also revealed that a PJI with a film of methanol on the orifice plate exhibited better ignition characteristics than one that was operated dry; this result was incorporated into the next experiment.

A more sophisticated cold chamber was constructed for the second experiment. It incorporated a refrigerated automotive-type electrically controlled fuel injector, turbulent cold air moving at between 4 and 10 m/s, and a multiple-shot 1 Hz firing system. The plasma jet power supply was modified to provide energy levels in steps up to 20 Joules. A plasma jet ignitor was modified by adding a sintered bronze end in order to eliminate firing variations caused by plug wetting. This device would appear to have some merit as a starting improvement on its own, although further in-engine testing is needed. Initial tests of the experimental setup showed that the plasma jet ignitor would ignite methanol droplets when fuel and air temperatures were near -25 °C; many experimental runs at temperatures between 0 °C and -24 °C confirmed this, and produced a well-defined family of curves of energy vs the percentage of shots lighting. A plot of energy values for which 80% or better ignition rates were achieved at each temperature shows a linear relationship in which ignition energy increases as temperature decreases.

For the third experiment, a 1973 Volvo sedan with 189,000 km on the engine was fitted with an alcohol fuel system, plasma jet ignitors, a high-energy rubbing contact distributor, and a high energy power supply. Before the ignition retrofit, an initial test of the engine running on M100 fuel with its standard J-gap spark plugs and standard ignition system showed that starting was impossible at block temperatures below +18 °C. Using the high-energy plasma jet power supply on the J-gap plugs only improved the starting temperature to +15 °C, with an energy of 1.9 Joules. The engine eventually failed completely to start at a temperature of 12.5 °C with an energy of 8.45 Joules. When this test was concluded, with the block temperature at 7.5 °C, plasma jet ignitors were substituted for the J-gap plugs, and starting was achieved in 5 seconds using an energy of less than 1 Joule.

Cold starting tests of the plasma jet ignition system and M100 fuel were conducted over a period of several weeks. The car was left outdoors the entire time, and no block heater or other assist device was used. Starting procedure was 10 seconds of cranking followed by 10 seconds of rest, with the energy level of the power supply being increased each time. The test was discontinued if no start had been achieved after 2 minutes elapsed time, or 60 seconds cranking time. When starting occurred, the energy needed at that temperature were recorded to form one data point. The graph (figure 3.13) of all data points shows a reasonably linear relationship between ignition energy and ambient temperature. -16 °C was the lowest starting temperature achieved (and operation was very rough), but firing was observed at -19 °C and -23 °C. The latter two data points lie approximately on the slope intercept line plotted on the average energy data for each temperature point. The -16 °C starting temperature observed in this experiment is believed to be the lowest recorded to date for an unmodified homogenous charge engine burning M100 fuel; a literature search and conversations with other researchers confirm this.

The use of methanol as a motor vehicle fuel is an idea which is gradually gaining acceptance and attracting development funding in many parts of the world, including Europe, Japan, and North America. There are several competing strategies, including M85 and M100. The switch to alcohol fuels is partially motivated by environmental concerns, and the buildup of greenhouse gasses in the Earth's atmosphere. Methanol is a much cleaner fuel than gasoline, and the introduction of methanol as a transportation fuel would greatly reduce the level of emissions of the three most common pollutants from automobile engines. However, the search for alternate fuels is also a product of the economic realities of petroleum. In the short term, fluctuating world oil markets and the use of the western world's dependence on oil as an economic weapon against the consuming countries are forcing transportation planners to consider alternative fuels. In the long term, a dwindling supply of petroleum products might well leave many world economies in chaos unless an alternative is available. Methanol is a good choice as an alternate fuel; it can be produced from both non renewable and renewable resources at a reasonable price, avoids the storage problems of the compressed gasses, and is relatively clean burning, which reduces the hardware cost of emission control devices. Cold starting of vehicles fueled with neat methanol is, however, a problem, since methanol vapourizes poorly at temperatures below +15 degrees. Although several cold starting strategies have been and are being investigated, none of these is wildly successful. The engine design showing the best cold starting performance, the DISC engine, has now been shelved because of poor emissions characteristics. For a homogenous charge engine, the lowest starting temperature recorded previously in the literature is -6.5 °C.

The results of the experiments described in this thesis show clearly that the plasma jet ignitor, run at high energies, will ignite neat methanol fuel at temperatures well below zero. A plasma jet ignition system, using the same technology, improved sub-zero starting on M100 fuel at sub-zero temperatures, even with an old engine in less than ideal condition. Ignitor erosion is a problem at the high energies used; however, the use of a very high voltage system would reduce this problem considerably. Further research may show the plasma jet ignitor to be a practical and cost effective method of cold starting M100 fueled automobile engines, either by itself or used in conjunction with some other strategy. If so, its use would overcome one of the chief stumbling blocks now facing the widespread introduction of neat methanol as a transportation fuel, especially in colder climates. The results of these experiments are promising, and are certainly a starting point for further research.

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APPENDIX 1: PLASMA JET IGNITOR EROSION

Erosion is one of the most serious drawbacks of the plasma jet ignitor. As mentioned in Section 2.4, erosion rates vary from 20-25 micrograms/Coulomb for hardened steels to 30-40 micrograms for mild steel. The major problem area is, of course, the orifice, although cavity erosion can also occur. Also mentioned in section 2.4 was the reduction in the number of Coulombs of charge passing through the ignitor obtainable by going to a discharge of 20,000 volts or higher. Erosion varies directly with the number of Coulombs discharged through the ignitor; an all-high-voltage discharge would theoretically reduce the amount of charge passing the ignitor by a factor of about 20, and presumably reduce erosion by a similar amount. To test this theory, an erosion test was done using a standard plasma jet ignitor, as described in Section 2.1, and the all-high-voltage power supply described in Section 2.4.

The test was designed to put the equivalent of approximately 40,000 km (25,000 miles) of operation of wear on the ignitor, assuming that 1500 shots per mile would be fired. Thus, approximately 37.5 million shots, or 75 million discharges were required to simulate the 25,000 kilometers of operation. Each 1 Joule shot would cause two discharges: the first discharge when the power supply was fired, and the flyback discharge immediately afterwards. The first discharge averaged 13-16 kV when the test began, but after 13 hours climbed to an average of 21 kV, where it remained for most of the rest of the test. The flyback discharge began at 4-5 kV but climbed to 9-10 kV later on. The flyback voltage was somewhat erratic during the latter part of the test. The output capacitance was 1710 picofarads throughout.

Two methods were used to check on the number of shots fired. First, an event counter was connected to the trigger system, and entered one event for each trigger pulse. Second, a stopwatch was run whenever the test unit was operating, and the trigger frequency kept between 50 and 51 Hz. Multiplying the elapsed time by the trigger frequency gave a reasonable check of the total number of shots. A Wavetek Model 187 Function generator was used as a trigger pulse generator, and the battery supplying 12VDC to the ignitor power supply was kept on charge throughout. This ensured that the firing rate was as consistent as possible.

The ignitor under test was fired in a small test cell through which dry compressed air was bled at a constant rate. The pressure was held constant at atmospheric (i.e. 0 gauge pressure), since pressure changes were found to alter the discharge characteristics of the plug somewhat. The test was done in sections, and stopped periodically for a few moments so that the ignitor could be visually inspected. Otherwise operation was as continuous as possible. The plug was mounted in a carrier, so that physical handling would not alter the weights of the components in any way.

The total elapsed time of the test, all sections, was 205 hours and 25 minutes. 37,530,000 shots were fired, causing approximately 75 million breakdowns. At 1500 shots per mile, this works out to 25,020 miles or 40,250 km. Orifice wear was visibly noticeable at 24.52 million shots (189.5 hours), and the plasma plume was observed to be much shorter and weaker than it was initially. The most visibly eroded area was on the orifice edges; both inner and outer edges were badly rounded, with the inner being worse. The cavity walls also showed signs of erosion, especially where the ceramic insulator end butted against the steel orifice. However, the breakdown voltage remained relatively constant even after erosion became visible.

Before the test ignitor was assembled, the three parts which would erode (metal orifice body, ceramic insulator, tungsten center electrode) were weighed on a microgram balance. After the test was completed, the parts were again weighed on the same balance. The results are as follows:

PART	INITIAL WEIGHT (gm)	FINAL WEIGHT (gm)	WEIGHT LOSS (gm)
ORIFICE	50.6860	50.6320	0.0540
CERAMIC	34.9969	34.8860	0.1109
ELECTRODE	6.1625	6.1481	0.0144

The total erosion was thus 0.1793 grams. The loss rate, determined by dividing the total weight eroded, 0.1793 gm, by the number of discharges, 75 million, comes out at 15.7 micrograms/Coulomb. This overall figure is comparable to the 20-25 microgram/Coulomb results mentioned at the beginning, if one takes into account the presence of very hard tungsten, and somewhat softer hardened steel and ceramic. It is also interesting to note that weight lost from the steel orifice plate, 0.0540 grams, is approximately 3.86 times that lost from the tungsten electrode, 0.0144 grams. Since these two pieces form the two ends of the discharge path, it is clear that ignitor life can be extended by making both pieces out of as hard a material as possible. Cavity erosion, which accounts for the majority of the material lost, could likewise be improved by using a harder and higher-temperature ceramic material.

The object of this erosion test was to confirm that using an all-high-voltage power supply would improve the life of a plasma jet ignitor to the point where it could be considered for operation in a normal engine. In this respect the test was successful; 40,000 km or 205 hours is a vastly improved lifetime for a plasma jet ignitor when compared to the 10-20 hour life span encountered with an ordinary plasma ignitor power supply (Section 2.3). This result is a good argument for adopting the PJI in applications which were previously impractical because of the PJI's erosion characteristics, regardless of the fuel type involved.

However, this successful result adds another facet to the idea of using a plasma jet ignitor in an engine burning M100. Since high energy levels (10+ Joules), would only be needed for cold starting, with energies of 0.5 to 1 Joule (as provided by the power supply described in Section 2.4) being quite adequate for warm-engine operation, a low voltage (1000 volt) "starting booster" power supply could be added. The finished product would resemble a "super" version of the power supply described in Section 2.3. The high voltage (30 kV) side would be a system similar to that described in Section 2.4, and the low voltage (1000 volt), high power side would be turned on only for starting. The 30 kV side would thus produce about 1 Joule, instead of 30 millijoules, and the 1000 V side might go as high as 15-20 Joules. In this way, component costs could be reduced, since all components would not have to be rated for the high energy levels, and erosion also kept at a minimum.